UTILIZATION OF LOW NO_x COAL COMBUSTION BY-PRODUCTS

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ABSTRACT

Low NO_x combustion practices are critical for reducing NO_x emissions from power plants. These low NO_x combustion practices, however, generate high residual carbon contents in the fly ash produced. These high carbon contents threaten utilization of this combustion by-product.

This research has successfully developed a separation technology to render fly ash into useful, quality-controlled materials. This technology offers great flexibility and has been shown to be applicable to all of the fly ashes tested (more than 10).

The separated materials can be utilized in traditional fly ash applications, such as cement and concrete, as well as in nontraditional applications such as plastic fillers, metal matrix composites, refractories, and carbon adsorbents. Technologies to use beneficiated fly ash in these applications are being successfully developed.

In the future, we will continue to refine the separation and utilization technologies to expand the utilization of fly ash. The disposal of more than 31 million tons of fly ash per year is an important environmental issue. With continued development, it will be possible to increase economic, energy and environmental benefits by re-directing more of this fly ash into useful materials.

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SUMMARY

Fly ash is generally classified as Class C or Class F depending upon the type of coal from which it is derived. Low sulfur Western lignites, for example, produce Class C ash readily which is high calcium and possesses high pozzolanic and cementitious activities. Bituminous coals produce Class F ash which is lower in calcium and also possesses pozzolanic activity. Some utilities burn mixtures of coal that result in mixtures of C and F ash.

At present, the largest single market for fly ash is as a replacement for cement used in concrete applications. Of the 54 million tons of ash generated annually only 25% is utilized commercially. The remaining 30 million tons is disposed mostly in landfills and represents a serious environmental problem. Many utilities are facing difficulties with ash disposal. The problem will only exacerbate as the amount of unsaleable ash increases as utilities strive to meet NO_x emission commitments. In general, the lower the NO_x emissions, the higher the unburned carbon content of the resulting ash. Typically, power plants using low NO_x burners experience a 3 to 6 percentage point increase in the unburned carbon content of their fly ash. Carbon is a detrimental material for fly ash in concrete applications.

This study had two major objectives. The first was to develop a separation process to yield high quality fly ash materials. The second was to develop new high value applications and markets for fly ash. An approach to fly ash processing was developed to produce four major products; cenospheres, magnetics, carbon, and clean ash.

Flotation is central to the process developed to remove carbon from fly ash. Typically clean ash with a carbon content (LOI) of 0.4%, in contrast to 21.7% in the as-received fly ash was produced. The magnetic concentrate contained 77.2% iron oxide. The carbon concentrate had a carbon content of 67.7%. Further work needs to be done to raise the carbon content by liberating additional carbon from the accompanying mineral contamination. One way of doing this is to grind the carbon to a finer size and run it through additional flotation steps.

Five generic areas have been identified as potential markets for utilization of separated, quality-controlled fly ash products. They are 1) cement and concrete, 2) ceramics and refractories, 3) plastic fillers, 4) metal matrix composites, and 5) carbon adsorbents. Each area has the potential to consume a large volume of fly ash. The cement industry, for example is a 76 million ton annual business of which up to 20% has been estimated as replaceable with fly ash if the composition is consistent and low in carbon content.

Some applications such as ceramics and activated carbons are high-value-added applications. The ceramic and refractory product markets represent about 40 million tons of finished products per year. Possibly more than 2 million tons of fly ash could enter this market. Mineral fillers represent a market of about 17 million tons of material annually. Approximately 8 million tons of this total is consumed by the plastics industry. Fly ash already represents a portion

of this market, but further penetration by fly ash has been limited by the lack of its availability with acceptable characteristics. It is estimated 2 million tons of froth flotation processed fly ash would be readily marketable as a plastic filler each year. Potential high value uses for the recovered carbon from fly ash include the 250 million pound annual activated carbon market and the several million ton carbon black market. A certain market for the carbon is as an industrial fuel or reducing agent.

Cenospheres (specific gravity 0.64) have traditionally been recovered as “floaters” from ash settling ponds. They have a number of well-established markets, including lightweight plastics, insulating panels, golf balls, autobody fillers, and PVC floor coverings. Their utilization is not revisited in this study. Iron oxide spheres can be utilized in heavy media separation processing such as commonly practiced by coal cleaning operations. No new technology was investigated in this study for these fly ash components.

It is encouraging to note that all of the 28 day strengths of clean ash concrete exceeded the basic design strength of 3500 psi. This assures the traditional concrete market for cleaned ash. All fresh concrete mixtures require a certain amount of air. It is important for there to be air in concrete to improve the workability of the fresh cement mixture, increase the impact strength of concrete, and improve the freeze/thaw behavior of the concrete. When as-received, high-carbon ash is added into the mixture, carbon particles in the ash adsorb the air entraining agent in fresh concrete because of their high specific surface area and sorption capacity, which decreases the air content in the concrete. After carbon removal by the beneficiation process, the air content in the cleaned ash-cement-water mixture is restored.

Low NO_x ash was successfully processed to produce fine clean powders with the characters suitable for plastic filler application. The particle size distribution is narrower than that of two comparable commercial fillers. Fly ash brightness is much lower than that of commercial calcium carbonate filler and alumino-silicate filler and would have to be taken into consideration prior to its commercial use. The unique spherical shape of fly ash allows molding to be accomplished at lower temperatures and pressures. These less severe operating conditions result in reduction of energy costs of production and reduces equipment wear in comparison to the use of conventional fillers.

Polypropylene, low density and high density polyethylene compounds with fine clean ash filler have equivalent or better moldability when compared to a commercial calcium carbonate filler. In general, polypropylene and high density polyethylene with fine clean ash filler show equivalent or better strengths and Young's modules, but the elongation is not as good as that experienced from the use of a commercial calcium carbonate filler. The mechanical properties of low density polyethylene with the fine clean ash filler were superior to moldings made with the same polymer and calcium carbonate filler, regardless of loading level.

Fly ash has a chemical composition and consistency similar to clay. Both materials are aluminosilicate compounds and are powdery when dry. Because of these features fly ash has the potential replacing part of the clay in many clay products. Although beneficiation of fly ash adds processing costs to the use of ash, cleaning may make it more suitable for use in the manufacture of more advanced materials such as mullite, an advanced ceramic capable of being synthesized from silicates and alumina. Mullite rarely occurs in nature and is generally produced by fusion of alumina and silica in an electric arc furnace. Currently, mullite sands sell for \$1,500 - \$1900 per ton depending on particle size and the synthesis route. The materials for synthesis include alumina, silica and clay which are priced at about \$1,000, \$20 and \$60 per ton respectively. Beneficiated fly ash is estimated to cost less than \$20 per ton. Since it contains 30% alumina, a 1 to 1 ratio of fly ash to alumina is required to synthesize mullite compared to a 2 to 1 alumina ratio if silica is used. Obviously the lesser requirement for alumina with fly ash synthesized mullite translates into a considerable cost savings. Class C fly ash can not be utilized to synthesize mullite material because the occurrence of high levels of calcium and sodium significantly reduce the refractoriness of the resulting mullite. In addition, as-received Class F fly ash is not suitable for synthesizing low thermal expansion coefficient mullite materials. However, fly ash beneficiated by the process developed in this research can be utilized to synthesize mullite with water absorption, density, refractoriness, thermal expansion coefficient, and fracture toughness that are comparable to commercial mullite material.

Activated carbon is a solid that has an extremely large internal surface area and pore volume. These characteristics and the affinity of carbon for a wide range of organic and inorganic materials are responsible for the use of activated carbon in production processes and environmental situations. None of the fly ash recovered carbons produced Iodine Numbers (a measure of adsorption) as high as commercial products. This may be attributed to the high ash content (over 30%) of fly ash activated carbon, suggesting that further cleaning of the carbon concentrate may improve its quality.

The use of fly ash carbon to capture mercury from coal combustion flue gas effluent was not designed to be part of the coal combustion by-product utilization project. Nevertheless, work was undertaken in the project because of the importance of controlling mercury in the environment and its relationship to fly ash and the electric utility industry. Initial results show that fly ash carbon may have a mercury adsorption capacity several times higher than commercial activated carbon for coal combustion flue gas cleaning. Additional work needs to be undertaken to more fully understand the adsorption mechanisms of mercury on carbon and to determine how carbons from coal combustion can be treated for uniform and consistent performance.

Aluminum metal matrix composites represent an attractive, high-value-added, future market for processed fly ash. Over the last decade, discontinuously reinforced aluminum metal matrix composites have emerged as potential engineering materials for applications in a number of markets, including automotive, aerospace, electronic packaging and recreational products. These composites consist of a metallic aluminum matrix reinforced with blended-in hard ceramic

particles. Aluminum composites exhibit very attractive engineering properties, but they currently cost substantially more than alternative engineering materials. Accordingly, there is a well-recognized need to reduce the cost of aluminum composite materials.

Many current composites are produced using relatively expensive alumina or silicon carbide reinforcements. Accordingly, work was undertaken to assess the potential for using cleaned, sized fly ash as a low-cost alternative for these higher-cost ceramic additives. As-received ash, with its high residual carbon content and wide particle size distribution, is not well-suited for most composite applications. The residual carbon, due to its porous morphology, is likely to degrade material properties significantly and the wide particle size distribution promotes inhomogeneous mixing of the metallic and ash phases. Ash beneficiation, however, can overcome these limitations. These results demonstrate that fly ash can be used effectively as a reinforcing phase in powder-metallurgy-based aluminum composites. With appropriate processing, the materials possess tensile properties competitive with traditional aluminum powder metallurgy materials while exhibiting excellent potential for substantially-improved wear performance. In order to fully exploit the cost-savings potential of these composites in applications such as wear inserts for automotive aluminum castings, however, there is a need to further develop low-cost processing protocols for the material.

Introduction

The 1990 Clean Air Act Amendments established limits on sulfur dioxide emissions and called for a two phase 2 million ton reduction of nitrogen oxides (NO_x) emissions relative to 1980 levels. Compliance dates for coal combusting electric utilities were the year 1995 for Phase 1 and the year 2000 for Phase 2, depending on boiler type and location, i.e. ozone nonattainment areas. Many coal-fired utilities have chosen retrofitting with low NO_x burners as their strategy for meeting their share of the 1990 requirements. This increased use of low NO_x burners however, has had a significant impact on the utilization of fly ash, a coal combustion by-product.

According to a 1996 survey by the American Coal Ash Association (ACAA), low NO_x combustion generates 5 to 11 million tons of fly ash per year. The total amount of fly ash generated from coal-fired utilities was about 54 million tons. The survey also found that low NO_x ash is generally not marketable because it has higher and more variable levels of unburned carbon than conventional ash. ACAA estimates that the advent of low NO_x technology and the resulting unsaleable ash costs deprives utilities of \$125 to \$275 million per year in sales, costs ash marketers \$100 to \$200 million per year, and increases the material costs of ash users by \$125 to \$275 million per year [1]. This problem will be even more serious as the year 2000 approaches and the tonnage of low NO_x ash increases as utilities make changeovers to meet Phase 2 compliance.

At present, the largest single market for fly ash is as a replacement for cement used in concrete applications. The pozzolanic properties of fly ash have made it a valuable material for this market. ASTM standard C618 has set a maximum limit of 6% LOI (primarily carbon) for fly ash used in place of cement. In practice, a 3% LOI limit is commonly recognized by the market.

Theoretically, combinations of higher oxygen and higher combustion temperature would decrease the carbon content of fly ash generated in a low NO_x combustion unit. However, this is not practical because low NO_x combustion requires low oxygen and/or low temperature combustion conditions. Thus, it is generally recognized that the lower the NO_x emissions, the higher the unburned carbon content of the resulting ash. Typically, power plants using low NO_x burners experience a 3 to 6 percentage point increase in the unburned carbon content of their fly ash [2-5].

According to the ACAA, of the 54 million tons of ash generated annually only 25% is utilized commercially. The remaining 30 million tons is disposed mostly in landfills and represents a serious environmental problem. Many utilities are facing difficulties with ash disposal. The problem will only exacerbate as the amount of unsaleable ash increases as utilities strive to meet Phase II NO_x emission commitments.

There is a need to increase the commercial utilization of fly ash to address the disposal problem and to bring about other environmental benefits. For example, when a ton of ash is used

to replace cement in concrete, 0.8 ton of CO₂ emissions associated with cement production is eliminated. At present, transportation costs generally limit the utilization of fly ash to within 150 miles of its point of generation. An increase in the value of fly ash is necessary if its utilization rate and the distance from point of generation to markets are to increase.

Objectives

This study had two major objectives. The first was to develop a separation process to yield high quality fly ash materials. The second was to develop new high value applications and markets for fly ash.

A processing approach to accomplish four major separations as depicted in Exhibit 1 was adopted to accomplish the basic project objectives.

Exhibit 1 Generic Fly Ash Flotation Processing

Physical characterization of the fly ashes studied in the project consisted of fundamental physical property determinations, chemical analysis and microscopic observations. Fly ash from American Electric Power, Nevada Power and Detroit Edison were processed all the way through pilot flotation plant processing and process waters were analyzed for potential water discharge problems when the flotation process is commercialized.

Fly ash is generally classified as Class C or Class F depending upon the type of coal from which it is derived. Low sulfur Western lignites, for example, produce high calcium class C ash readily accepted by cement users because of its high pozzolanic activity. On the other hand, high sulfur coals produce Class F ash with generally less pozzolanic activity and higher carbon contents. Many utilities, especially those in the eastern United States burn mixtures of coal that result in mixtures of C and F ash.

The project focused on four ashes, a Class F from American Electric Power (Glen Lyn), a Class C from Nevada Power, a second Class F from Baltimore Gas & Electric and a mixture of C and F from Detroit Edison (River Rouge Unit #2). Other ash from Western Massachusetts Electric (Holyoke), Pennsylvania Power (New Castle), and a second Detroit Edison ash were partially characterized but did not receive as extensive investigation as the aforementioned ashes.

The most extensive work was done with ash from American Electric Power, Baltimore Gas & Electric, and Nevada Power because these utilities use the three most popular low NO_x burners. American Electric Power (AEP) supplied twenty three 55-gallon drums of fly ash from their Glen Lyn plant where a single wall fired-dry bottom boiler made by Babcock & Wilcox burns 1,523 mlb of eastern coal per hour. NO_x control in their type of boiler is by staged combustion technology.

Baltimore Gas & Electric (BGE) uses an opposed dry bottom burner made by Babcock & Wilcox. The capacity of the burner is 4,425 mlb/hr. NO_x control is by staged combustion technology, the fifth largest NO_x control method. BGE burns bituminous, low sulfur coal from West Virginia. Fourteen 55-gallon drums of fly ash from BGE were received.

Nevada Power (NP) uses a front-dry bottom made by Foster Wheeler Energy with a capacity of 2,090 mlb/hr. NO_x control with this type of burner is obtained by boiler design. Boiler design is the third largest NO_x control method. NP burns sub-bituminous, low sulfur coal from Utah. Fifteen 55-gallon drums of fly ash from Nevada Power were received.

Each of the as-received fly ashes were subjected to preliminary analysis to determine a LOI value, a sieve analysis of the +400 mesh fraction and a Microtrac analysis of the -400 mesh fraction. Chemical analysis was performed on each size fraction to determine the significance of elemental distribution. This information was necessary to determine how to process the ash to obtain the most uniform feed materials for subsequent processing into commercial products.

The amount of magnetic material in the as-received ash was determined using a Davis Magnetic Tube Test. This is a method where particles of a material are held in suspension with a flow of water and subjected to a magnetic field to separate materials into magnetic and non magnetic fractions. Fly ash magnetics are known to have value as a source of iron units for steel production and as a heavy media in certain coal cleaning processes.

Based on the characterization results, a fly ash separation process has been designed and tested as depicted in the flow sheet of Exhibit 2. The process consists of a gravitational process to collect cenospheres, a magnetic process to remove the iron oxide spheres, and froth flotation to separate the unburned carbon [6, 7]. The remaining material after these separations is designated as clean ash. Depending on user needs, individual process separation circuits can be sequenced, eliminated, or new circuits can be added. This offers great flexibility to meet separation requirements dictated by varying ash component ratios as for example a utility varies combustion conditions because of fuel switching or changes in power demands.

Exhibit 2 Fly Ash Beneficiation Flowsheet

In some instances, for example, a froth flotation circuit may be all that is needed for ash processing if the material is to be used only for cement replacement. Magnetic separation would have to be included if the cleaned ash is to be used for refractory applications. If the clean ash is to be used for plastic filler applications, a hydrocyclone circuit would be required to separate the clean fly ash particles into appropriately sized fractions.

Material Characterization

Chemical characterization studies for the fly ash project were carried out using Scanning Electron Spectroscopy (SEM) coupled with an Energy Dispersive Spectrometer, Inductively Coupled Plasma (ICP), and X-Ray Diffraction (XRD). Scanning Electron Microscopy was utilized to identify sample morphology along with qualitative and quantitative chemical analysis. Inductively Coupled Plasma was used for quantitative chemical analysis for the fly ash samples and products and chemical analysis for metals and semi-metals existing in the process waters during the beneficiation process. X-Ray Diffraction spectra was analyzed to identify mineralogical constituents present in the fly ash as received and the beneficiated products.

Chemical analysis of the as-received ashes at different screen sizes is shown in Appendix 1. The clean ash analyses are given in Appendix 2. LOI analysis by size fraction is presented in Exhibits 3 and 4. In all cases the loss on ignition (LOI) is highest in the largest particle size fraction and decreases with the smaller particle sizes (signifying carbon concentration in the larger particles). Adversely the major oxides in the samples are at the lowest concentrations in the larger screen specimen samples. The trend with the clean product was the same as with the as- received samples; larger particles had a greater LOI value.

As expected, the clean product had considerably less LOI values due to the product being largely cleaned of the carbon present in the as received samples. One conspicuous note is that calcium oxide was on the whole at highest concentrations at the smallest particle size. Trace elements for both the as received and cleaned fly ash products can be viewed in the appendices. A total of 56 trace elements were analyzed using the spectrum of the ICP.

Chemical characterization of the various size fractions is important in designing the appropriation beneficiation process to achieve desired cleaning results. For example when the LOI data by size fraction for the various four fly ashes is examined, it is seen that unburned carbon (LOI) can not be lowered by sieving without removing considerable amounts of the silica and alumina portions of the ash.

Exhibit 3 LOI by Size Fraction of As-received Fly Ash

Exhibit 4 LOI by Size Fraction of Clean Fly Ash

Overall % LOI, size distributions, LOI by size analysis, and bulk density determinations were conducted on the as-received samples from AEP, BGE, NPC, and DE. The LOI and bulk density data is presented in Exhibit 5.

Exhibit 5 Fundamental Characteristics of As Received Fly Ash Samples		
Fly Ash Sample	Overall % LOI	Bulk Density g/cm³
AEP	22.2	2.13
BPG	6.4	2.24
NPC	4.0	2.25
DE	29.8	2.24

Water samples were collected during the beneficiation process at the carbon concentrate, clean ash product, and final process water sites. An ICP was utilized to determine the metal and semi-metal concentrations in the various water samples. A summary of the water analysis are presented in Exhibits 6 through 8. In all cases the process waters contain no alarming levels of heavy metals.

Other testing completed on the water were performed according to “Standard Methods For the Examination of Water and Wastewater.” Total residue, total filterable residue, total non-filterable residue, total volatile and fixed residue, and hardness. Detailed results from all water testing can be viewed in Appendix 3.

Exhibit 6 Water Analysis - Class F Fly Ash				
Contaminant	Drinking Water Standards Maximum Contamination Level (mg/L)	Carbon Stream (mg/L)	Clean Ash Stream (mg/L)	Fresh Water (mg/L)
Aluminum	0.05 - 0.2	0.1	2.4	0.55
Antimony	0.006	< 0.032	< 0.032	< 0.032
Arsenic	0.05	< 0.053	< 0.053	< 0.053
Barium	1.0	0.17	0.19	0.05
Beryllium	0.004	< 0.00027	< 0.00027	< 0.00027
Cadmium	0.005	< 0.0025	< 0.0025	< 0.0025
Chromium	0.1	< 0.01	< 0.0071	< 0.0071
Copper	1.0	< 0.0054	< 0.0054	< 0.0054
Iron	0.3	< 0.0046	0.07	0.03
Lead	0.05	< 0.042	< 0.042	< 0.042
Manganese	0.05	< 0.0014	< 0.0014	0.07
Mercury	0.002	< 0.025	< 0.025	< 0.025
Nickel	0.1	< 0.01	0.16	< 0.01
Selenium	0.05	0.25	0.09	< 0.075
Silver	0.1	0.01	0.02	0.02
Thallium	0.002	< 0.040	< 0.040	< 0.040
Zinc	5	0.39	3.04	0.1

Exhibit 7 Water Analysis - Class C Fly Ash				
Contaminant	Drinking Water Standards Maximum Contamination Level (mg/L)	Carbon Stream (mg/L)	Clean Ash Stream (mg/L)	Fresh Water (mg/L)
Aluminum	0.05 - 0.2	0.24	0.42	0.55
Antimony	0.006	0.03	0.06	0.07
Arsenic	0.05	< 0.053	< 0.053	< 0.053
Barium	1.0	1.08	1.66	0.07
Beryllium	0.004	< 0.00027	< 0.00027	< 0.00027
Cadmium	0.005	< 0.0025	< 0.0025	< 0.0025
Chromium	0.1	0.38	0.18	< 0.0071
Copper	1.0	0.03	0.08	< 0.01
Iron	0.3	0.31	0.4	0.04
Lead	0.05	< 0.042	< 0.042	< 0.042
Manganese	0.05	< 0.0014	< 0.0014	0.06
Mercury	0.002	< 0.025	< 0.025	< 0.025
Nickel	0.1	0.02	0.04	< 0.01
Selenium	0.05	0.23	0.31	< 0.075
Silver	0.1	0.01	0.01	0.02
Thallium	0.002	0.17	0.14	0.25
Zinc	5	1.09	1.95	0.29

Exhibit 8 Water Analysis - Class C/F Mixture Fly Ash				
Contaminant	Drinking Water Standards Maximum Contamination Level (mg/L)	Carbon Stream (mg/L)	Clean Ash Stream (mg/L)	Fresh Water (mg/L)
Aluminum	0.05 - 0.2	8.72	41.67	< 0.023
Antimony	0.006	< 0.032	< 0.032	< 0.032
Arsenic	0.05	< 0.053	< 0.053	< 0.053
Barium	1.0	0.17	0.10	0.06
Beryllium	0.004	< 0.00027	< 0.00027	< 0.00027
Cadmium	0.005	< 0.0025	< 0.0025	< 0.0025
Chromium	0.1	0.17	0.60	< 0.0071
Copper	1.0	< 0.0054	< 0.0054	< 0.0054
Iron	0.3	< 0.0046	< 0.0046	< 0.0046
Lead	0.05	< 0.042	< 0.042	< 0.042
Manganese	0.05	< 0.0014	< 0.0014	0.06
Mercury	0.002	< 0.025	< 0.025	< 0.025
Nickel	0.1	0.03	0.03	0.03
Selenium	0.05	0.45	0.97	< 0.075
Silver	0.1	0.01	0.01	0.01
Thallium	0.002	< 0.040	0.09	< 0.040
Zinc	5	0.90	< 0.0018	0.12

Separation Technologies

A material has reasonable commercial value only when it is well defined and meets industrial specifications. It must also be available at consistent quality levels and in sufficient quantities to meet market demands. Characterization of fly ash obtained from various sources shows that the mineral components of the ashes are similar, even their bulk chemistry may vary widely. Based on scanning electron microscope studies (Appendix 4), the major mineral components in fly ash can be categorized as silicates, iron oxides, and low density silicates (cenospheres). The silicates are usually present as spherical particles. They are believed to be the melted products of clays, feldspars, quartz, calcite, and other common minerals in the coal from which they originate. The iron oxides are usually spherical magnetite and are believed to be derived from pyrite, hematite, siderite, and limonite in the coal. Low density silicates are frequently high alkaline silicates which entrapped gas during their formation to yield hollow spherical particles. Unburned carbons are generally chars with irregular shapes and a wide range of particle sizes. Variations in the ratios of these components generally result in variations in fly ash bulk chemistry.

Laboratory Testing of Flotation Operations

Laboratory work was conducted to evaluate flotation parameters and their effect on the resulting clean ash and carbon concentrates. Initial work had previously been conducted with the AEP, BGE and NPC fly ashes. The work was accelerated under the current project when AEP and NPC expressed interest in possible commercialization of the separation process. Considerable ash from these utilities was eventually processed for product testing as described in later sections of this report. The parameters investigated during the laboratory phase of the project included pulp density, conditioning time, collector type and dosage, frother type and dosage, and pH adjustment. Detailed laboratory test data results are presented in Appendix 5. The tests are sorted based on the cell product (clean ash) % LOI. For the NPC ash flotation program, % carbon was measured rather than the % LOI because constituents of Class C ash hydrate when placed in water resulting in an elevated LOI value.

The range of carbon values in the Class C clean ash was much narrower than the Class F ash, from 1.03 to 2.78% C. For the AEP ash (Class F), the range of clean ash % LOI was quite broad, from 0.06% up to 24.96%. The flotation parameters included several collector dosages, several frother dosages, one or five minute conditioning times, and solids fractions of 10, 18, and 25%.

The effect of pH adjustment on flotation results was not tested for the NPC fly ash (Class C). Initial tests showed that it was difficult to bring the pH to neutral and to hold it there during the tests due to the high lime content of this ash, thus it was decided to eliminate pH adjustment as a variable for the NPC ash. For the AEP testing, the target values of $\leq 2\%$ LOI and $\geq 50\%$ weight recovery in the clean ash were achieved at a natural pH.

Ancillary Operations

The flotation circuit parameters are fairly well defined, however, that process would be of little use to industry without the ability to handle and treat the ash before and after flotation. Many of the ancillary operations such as dewatering, drying, and size separation (both before and after flotation) have not been studied in detail. This section describes the laboratory scale tests that were conducted to provide valuable preliminary information for process scale up and plant design options.

Dewatering

The dewatering and drying processes, although they have little effect on the nature or quality of the resulting fly ash and carbon products, have a tremendous impact on the overall economics of the ash beneficiation process. Since drying accounts for approximately one third of the total cost of operating an ash beneficiation facility, there is considerable incentive to use mechanical means to concentrate the solids and reduce the amount of water prior to drying.

Settling Tests

In the minerals processing industry, "sedimentation" refers to a broad spectrum of processes which are based on the principal that solid particles, of greater density than the liquid in which they are suspended, will settle to the bottom of a vessel. The most widely used piece of equipment using sedimentation as the principal means of concentrating the solids contained in a slurry is a cylindrical thickener.

A series of settling tests, to assist in the determination of thickener capacity requirements, were carried out using both AEP and NPC ash and carbon fractions. These tests are used to establish the settling rates of each material at various pulp densities. This series of tests involved monitoring of a "mud line", which indicated the level to which the pulp had settled out, in a large graduated cylinder initially filled with a slurry of the material being tested. The solids content of the slurry was varied from 5% to 30% with each ash tested and from 5% to 15% for each carbon tested. The results of these tests are given in Appendix 6.

The results of the settling tests were then used to determine the unit area required to thicken a ton of dry solids. Utilizing the procedure developed by Coe and Clevenger, [8] the settling rate of the solids were established for both the clean ash and the carbon concentrates obtained from processing AEP and NPC ash. Using the following equation and data from AEP ash settling tests, thickener diameter for a 15 ton per hour processing plant was determined.

$$A = (1.33 (F - D)) / R$$

Where:

- A = Thickener area in square feet per ton of dry solids thickened in 24 hours
- F = Initial density (parts water to solids by weight)
- D = Final density to which pulp will be settled
- R = Settling rate in feet per hour

The settling tests indicated that the settling rate of the limiting pulp density was about 8.3 ml/min or .91 ft/hr. The initial density from the flotation circuit into the thickener would be about 4.5 (parts water to solids) and the final density would be about 1.5 (parts water to solids). Using the above formula, the required area per ton of material thickened in 24 hours would be 4.38 ft²/t*hr. Thus, a thickener with a 45 foot diameter would be sufficient for a 15 tph plant.

Use of a flocculant was also tested. Flocculants are high molecular weight, water-soluble polymers that can be added to the slurry to agglomerate the particles into relatively large lumps or flocs. In this series of tests, the flocculent was used in repeated tests involving the ash at 30% solids and the carbon at 15% solids. Use of the flocculent greatly reduced the settling time, however, there is some concern about the effect of residual chemical on the final ash and carbon products. This was not evaluated in this project.

After settling, the percent solids of the clean ash stream increased to 50% and the carbon concentrate increased to 30%. Further dewatering would be required.

Filtration

Filtration is the most common unit operation to follow thickening and serves to further reduce the moisture in the product. Aimed at simulating the conditions in a continuous vacuum filter, a filter leaf test circuit was assembled and tests were run on clean ash and carbon concentrate samples from AEP (Class F) and NPC (Class C).

The filter leaf assembly consisted of a section of filter media and a vacuum pump connected to a receiver flask, with a vacuum gauge to indicate vacuum in inches of mercury. While the filter leaf was subjected to a vacuum, it was submerged in the agitated pulp for a period of time. This "form time" represents that portion of a continuous cycle when the filter is forming a cake. Once the selected form time is complete, the filter is withdrawn from the slurry and rotated 180° to allow the filtrate to drain under vacuum, for a selected period of time (dry time). The filter cake was then removed, weighed and dried to determine the moisture content and cake production, in pounds per square foot, that are obtained under the various filtering conditions. The variables in this series of tests include form time, dry time, and filter cloth.

Form time had the most effect on the final moisture of the clean ash. In general, as form time increased, the resulting moisture decreased, indicating that the ash itself served as a good filter media. The filter cloth also had some impact on the final moisture. The test matrix included form times of 5, 10, and 20 seconds, with drying times ranging from 30 to 360 seconds. Data from these tests indicate that, with the AEP ash, a cake moisture of 17- 18% should be obtainable, whereas, with the NPC ash, a cake moisture of 21 - 22% could be expected.

Tests on the carbon concentrate were conducted in a similar manner. There was a difference in the cake formation between the AEP and NPC carbon samples. With a three second form time, the AEP carbon produced a cake weighing from 2.5 to 3.4 lb/ft², while the NPC

carbon cake required ten seconds to produce a cake weighing 0.86 lb/ft². Upon inspection, the NPC carbon had considerably more ash than the AEP sample, which may have affected the initial cake formation. The final cake moisture for the AEP carbon sample using a three second form time was 49.7%. The NPC carbon sample had a final cake moisture of about 42%, with a ten second form time.

In some applications, it is helpful to add hot air (410°F) or steam (300°F) to assist in the removal of moisture from the filter cake. A short series of tests were conducted to test this application for clean fly ash. From these tests, it was concluded that the addition of hot air or steam to the face of the cake during the drying period, although it served to reduce the final cake moisture (see Exhibit 9), did not reduce the moisture sufficiently to eliminate the need for thermal drying and would not be cost effective with the ash tested except in certain unique situations.

Exhibit 9 Effects of Hot Air and Steam on Clean Ash Filtration			
Filter Media	Ambient Air (90°F)	Hot Air (410°F)	Steam (300°F)
Cloth 1	17.11	17.01	14.90
Cloth 2	21.01	18.58	16.46
Cloth 3	17.98	16.98	16.89

Filter Press

While the leaf filter tests evaluated the operation of vacuum filtration on fly ash, other filtration options exist. Continuous filter presses are available from a number of manufacturers. Review of the literature showed that a moisture level below 15% could be achieved for thickened fly ash. After discussion with the companies and equipment users, a clean ash sample was sent to Filtra-Systems for testing in their 0.5ft² laboratory Verti-Press. The testing with a 46% solids slurry sample indicated that a 1" filter cake with a moisture content of less than 13% could be expected if the Verti-Press were used to dewater slurry from the clean ash thickener.

Centrifuge

Although thickening and filtration greatly reduce the moisture content of the product streams, two unit operations are involved. Preliminary tests indicate that using a centrifuge to dewater the ash can produce a cake with lower moisture in one operation.

An AML Industries, model 12-413V Lavin centrifuge incorporating either a solid bowl or a perforated bowl and a five micron filter cloth was used in the testing. The ash slurry, consisting of approximately one pound of ash being dispersed in about five gallons of water, was pumped into the system with a portion of the slurry being fed directly into the centrifuge and another

fraction recirculating back into the original feed material. By constantly recirculating a portion of the slurry the dispersion of the ash was maintained and no ash was able to settle out. The operation of the centrifuge continued until the recirculating stream became clear. At that point the centrifuge was stopped and the ash cake was removed. The moisture of the cake was then determined using conventional means.

A series of tests using a centrifuge to dewater the ash were carried out. The results from tests using the solid basket were very poor and this effort was discontinued. Tests using the perforated basket and filter cloth resulted in low moisture samples, as shown in Exhibit 10.

Exhibit 10 Centrifuge Test Results		
Ash Sample	Concentration (% Solids)	
	Initial	Final
AEP	15.0	91.2
NPC	15.0	89.6
BGE	15.0	89.0

Centrifuge tests indicated that the use of a centrifuge is a realistic option. The resulting products are good quality and low moisture, however, there are several factors that need to be evaluated before this technology is considered a viable option for dewatering ash. These factors include the abrasive nature of the ash and the economics of installing and operating the centrifuge.

Discussions were held with several centrifuge manufacturers regarding the dewatering of abrasive material. One company, Bird Machine, which is one of the largest manufacturers of centrifuges, has conducted pilot scale tests to dewater fly ash and also has existing installations that are dewatering alumina. They indicate that abrasives, such as ash, can be dewatered using the centrifuge without resulting in excessive wear along the surface of the bowl or scroll components of the centrifuge.

Another company, Heinkel Filtering Systems, has developed an automated method of removing the cake from the filter cloth lining the centrifuge basket. A fly ash sample was sent to Heinkel Filtering Systems for testing. The company guaranteed the cake from their filter/centrifuge system would reduce the clean ash moisture to below 10%. In the actual tests, using a feed slurry of 15% solids, the resulting cake had moisture levels between 7% and 8%. These tests were run with ambient air, the system could also incorporate hot air, which may allow us to eliminate the thermal drying portion of the process. This technology is very promising, however, the current machines are low capacity and expensive. Discussions with the company

indicate that larger capacity machines, at similar capital costs, are in the design stage. That would make this operation more economical and worth further investigation.

Discussions with industry and results from the preliminary testing indicate that the use of centrifuges to dewater ash should be considered in a fly ash beneficiation facility. Preliminary evaluation indicates that the capital cost of the centrifuge would be greater than for thickening and filtration equipment, the operating costs would be considerably less. Further evaluation of centrifuge technology for ash dewatering is recommended.

Drying

Many end use applications for fly ash require the ash to be dry. If the various dewatering methods described previously are unable to reduce the moisture content of the ash sufficiently, thermal drying will be necessary. There are many drying options available. One type of dryer that was studied in this project was a rotary tray dryer. A rotary tray dryer consists of a vertical chamber which encloses a number of trays stacked vertically and attached to a central axis. The moist cake enters the top of the dryer and is deposited on the uppermost tray as the tray revolves about the axis. With each revolution, the material is passed on to the tray below, until it is eventually swept from the lowermost tray and discharged from the dryer.

A series of preliminary tests were conducted by Wyssmont. The estimated costs associated with drying clean ash and carbon concentrate would be \$2.10 per ton of ash and about \$6.50 per ton of carbon. While this could be an acceptable cost for drying ash, it does not appear suitable for drying carbon.

A rotary tray dryer is only one of many types of dryers that could be used for drying products from the fly ash beneficiation process. Further testing is needed before final decisions can be made.

Hydrocyclone Tests

Several of the utilization options for clean fly ash require specific size fractions of the ash, generally the finer sizes. In the laboratory, an Acucut dry size separator has been used to produce the required size samples, however, this technology may not be the most economical to use on a commercial scale. Since the clean fly ash is in a slurry, tests using a hydrocyclone were conducted. A hydrocyclone is a classifying device that utilizes centrifugal force to accelerate the settling rate of particles. It is widely used as a classifier and is extremely efficient at fine separation sizes.

Preliminary hydrocyclone tests were run using AEP ash. These initial tests showed that a hydrocyclone can be used to separate the clean ash into various size fractions. Additional testing

is needed to determine the optimum operating parameters to reduce the particle size of the fraction being carried out the overflow of the cyclone, while making a cleaner cut.

Screening Tests

Tests were conducted to establish the parameters for dry screening the as-received ash prior to introduction into the wet beneficiation phase of the process. Initial results indicate that if an ultrasonic unit is attached to the screen, considerably greater throughput can be realized, at the same time, plugging of the screen can be nearly eliminated. Samples of as-received ash were sent to Russell-Finex and SWECO for testing.

Russell-Finex completed the requested tests at 325 mesh, with positive results, however the capacity was low. Since it is likely that, if used at all, the screening operation would employ a 100 mesh screen, the throughput would increase dramatically. This appears to be an ash specific unit operation.

The tests at SWECO indicated that, at the anticipated throughput of a commercial operation, the operating cost was much higher than could be tolerated. These systems work well on a small scale but the machine displayed excessive wear after being subjected to the highly abrasive clean ash fraction (alumina and silica) for extended periods of time.

Carbon Grinding

Small scale efforts were made to produce higher grade carbon concentrates with the introduction of a grinding mill into the cleaning stage of the flotation circuit. Different options for grinding the carbon have been studied and preliminary studies using the Vibrokinetic Energy Mill from Microgrinding Systems were successful. Further studies will be required to firmly establish the performance and economics of the VKE mill.

Conclusions

In the laboratory testing task, samples were evaluated for pilot plant operation, flotation variables were examined, and ancillary operations were studied. Much of this work was preliminary and further testing of the dewatering and drying options, in particular, is strongly recommended. Using mechanical dewatering and avoiding thermal processing can decrease overall capital costs. In addition, operating costs will decrease significantly - up to 40% - by reducing the energy/fuel costs associated with thermal drying. Several different methods are available to achieve this savings, more information would be extremely helpful in selecting the proper operations for the beneficiation circuit.

Flotation Machine Study

As part of this project, a PhD research program was conducted to study flotation machine effects on the fly ash beneficiation process. A dissertation titled "A Concurrent Flotation Column for Fly Ash Cleaning and Materials Separation: Its Design and Separation System Development" was completed. [9] The abstract from this dissertation follows.

In order to widely reuse fly ash, which was previously landfilled, the unburned carbons must be removed to below 1% in cleaned fly ash. Compared with electrostatic separation and gravitational concentration, froth flotation is the most effective approach to carbon removal. The performance of froth flotation depends on flotation equipment and its operation conditions. Generally, the optimal operation conditions may be decided by lab tests, however, for presently existing flotation machines, their weaknesses, such as high energy consumption and low unit throughput, may not be avoided. Thus, it is very critical to develop new processes and equipment that can minimize the operation costs of fly ash cleaning and improve separation efficiency.

The froth flotation process is an approximate first-order reaction as reported by many scientists and engineers. Hence, a concurrent flotation column, which can closely simulate a plug flow reactor, has a high potential to resolve the problems existing in commercial flotation machines. Based on the above considerations, a concurrent flotation column has been developed by combining a static mixer and froth separator. The static mixer acts as an air bubble generator and particle-bubble reactor while a froth separator works as a froth tail-slurry separator. A lab-scale concurrent flotation column was established using a square static mixer that was 5/8" x 5/8" x 72" long, and a froth separator that was 72" high with a 2" diameter. Corrugated plates were cut and used as the packing of the static mixer.

Experimental results have shown that the carbon removal under a concurrent flotation column with one static mixer is 22% below that of the Denver cell. Mechanism analysis showed that froth rupture might occur along a static mixer. The froth formation and breakage in a static mixer are reversible processes. Therefore, a perfect carbon removal could not be achieved using only one static mixer. Afterwards, dual static mixers were installed to add fresh air bubbles for recovering dropped carbon particles in the froth separator.

Using dual static mixers, the carbon removal was elevated slightly higher than that of the Denver cell. The concurrent flotation column shows an obviously higher throughput. Moreover, the energy consumption of a concurrent flotation column is only 20% of the Denver cell. This signifies that about 80% energy can be saved compared with conventional flotation machines. This breakthrough will also facilitate applications of concurrent flotation columns in other industries that are running froth flotation. Sieving results display that in all size ranges, material recoveries are very close for both the Denver cell and concurrent flotation machine. Still, the concurrent flotation column shows slightly higher selectivity for a fine material.

The size of air bubbles produced from a static mixer is significantly correlated to the surface tension, air flowrate and channel number of packings. Bubble size increases with surface tension, but decrease with the increase of air flowrate and channel number. Theoretical analysis also reveals that fine materials require more air for the same recovery of coarse materials. The increased rate of air required for floating dense materials is notably higher than the increased rate of materials' density.

There are a number of areas that should be addressed in future studies. Research on a static mixer should focus on the diverse packing size and shapes, and the size of a static mixer and its connections among the static mixers with various dimensions. The height and shapes of the froth separator, and a possible water addition should be further explored. In addition, the combination of a static mixer with a hydrocyclone, scale-up of static mixer and froth separator, and testing on diverse materials are also proposed.

In conclusion, the concurrent flotation column has proved to be a highly effective and efficient flotation device. Its extremely low energy cost and high unit throughput would significantly reduce the operation cost of fly ash cleaning, and potentially extend its applications in other industries.

Pilot Plant Testing

Pilot plant tests were run on AEP, NPC, and BGE fly ash samples, primarily to generate material for fly ash product development work described later in this report. Representatives from AEP and NPC were present to observe the pilot scale operations for their ash samples. Flowsheets from six pilot plant runs are given in Appendix 7.

Flowsheet Description

As outlined in the general flowsheet given in Exhibit 2, the ash was mixed with water at 20% solids content for processing in a pilot plant scaled to 200 lb/hr. The slurry was fed into a tank where the cenospheres floated to the top and were skimmed-off. Then it was run over a magnetic drum separator to recover magnetic spheres.

After magnetic separation, the slurry was conditioned with an oil collector at a dosage of 2 lb/ton. Oil has an affinity for carbon and is preferentially adsorbed onto the carbon particles. The oil conditioned slurry was then fed into a flotation machine where air was bubbled through it. Here the rising air bubbles collide with the oil coated carbon particles and attach themselves to these particles due to hydrophobic interaction. The carbon particles float to the top of the flotation cell, where they were skimmed off. Clean ash remained in the cell and is next filtered and dried. The carbon fraction was transferred to a second flotation cell and re-floated to upgrade the carbon by removing additional ash minerals. The reject from the carbon-refloat operation was returned to the first flotation cell.

Pilot Plant Test Results

A typical flotation trial produced clean ash with a carbon content (LOI) of 0.4%, in contrast to 21.7% in the as-received fly ash. The magnetic concentrate contained 77.2% iron oxide. The carbon concentrate had a carbon content of 67.7%. Further work needs to be done to raise the carbon content by liberating additional carbon from the accompanying mineral contamination. One way of doing this is to grind the carbon to a finer size and run it through additional flotation steps.

Exhibit 11 presents typical carbon removal results obtained on these ashes. It is significant to note that clean ash with less than 1% carbon content was obtained in all cases.

Exhibit 11 Carbon Removal by Froth Flotation				
Ash Type	Class F #1	Class F #2	Mixture C and F	Class C
LOI As-Received	21.70	7.25	4.35	4.00
LOI Clean Ash	0.40	0.61	0.90	0.96

Pilot plant test runs 1 through 4 were conducted on AEP ash. Run 1 was performed to shakedown the circuit and evaluate the location of the screening operation. Several modifications were made to the circuit design for Run 2, including moving the screening operation to just prior to flotation and adding two more stages of flotation for carbon cleaning. Mechanical difficulties were encountered during Run 3 and complete results were not obtained for that run. Run 4 was a repeat of Run 3. Runs 1 and 4 produced clean ash containing under 1% LOI (0.26% and 0.96%, respectively) while recovering slightly less than 60% of the initial weight of fly ash charged to the circuit. (The remaining ash was necessary to charge the processing circuit.) The clean ash LOI values for Runs 2 and 3 were 2.7% and 3.0%, respectively. This is with an ash that contained over 22% LOI prior to beneficiation. The carbon concentrates for all the runs were above 61% LOI, and with the exception of Run 1, the LOI of the carbon concentrates was between 68.8% and 69.9% LOI.

Run 5 involved BGE ash. The clean ash LOI value was 1.3% and over 70% of the initial sample weight was recovered, the balance was necessary to charge the flotation circuit. A carbon concentrate LOI value of 26.0% was obtained. Additional cleaner stages or optimization of the existing two carbon cleaner flotation stages would probably increase the LOI of the carbon concentrate.

NPC ash was tested in Run 6. Because this was a Class C ash, the % carbon was used as the primary target parameter rather than the % LOI. For comparison, the feed to the beneficiation process had a carbon content of 3.7%. The LOI determined for the dry, as-received sample was 4.0%. The pilot plant run produced a clean ash with a 1.2% C.

Other pilot plant runs were conducted on these materials, particularly the AEP ash, to obtain additional samples as needed for the utilization tasks. These subsequent runs used the circuit parameters developed in Runs 4, 5, and 6. They were not sampled in detail and are not discussed in this report.

Conclusions

Laboratory and pilot plant testing was primarily used to generate materials for applications testing. The general flotation circuit parameters are fairly well defined. Exploratory work was conducted on ancillary operations and alternative flotation methods. This work was successful but not developed further in this project.

Utilization Technologies

Five generic areas have been identified as potential markets for utilization of separated, quality-controlled fly ash products. They are: 1) cement and concrete, 2) ceramics and refractories, 3) plastic fillers, 4) metal matrix composites, and 5) carbon adsorbents. Each area has the potential to consume a large volume of fly ash. The cement industry, for example, is a 76 million ton annual business of which up to 20% has been estimated as replaceable with fly ash if the composition is consistent and low in carbon content.

Some applications such as ceramics and activated carbons are high-value-added applications. The ceramic and refractory product markets represent about 40 million tons of finished products per year. Possibly more than 2 million tons of fly ash could enter into this market. Fly ash use in mullite refractories was studied in a previous project. The results of this research is included for reference in Appendix 10.

Mineral fillers represent a market of about 17 million tons of material annually. Approximately 8 million tons of this total is consumed by the plastics industry. Fly ash already represents a portion of this market, but further penetration by fly ash has been limited by the lack of its availability with acceptable characteristics. It is estimated 2 million tons of froth flotation processed fly ash would be readily marketable as a plastic filler each year. Potential high value uses for the recovered carbon from fly ash include the 250 million pound annual activated carbon market and the several million ton carbon black market. A certain market for the carbon is as an industrial fuel or reducing agent.

Cenospheres (specific gravity 0.64) have traditionally been recovered as “floaters” from ash settling ponds. They have a number of well-established markets, including lightweight plastics, insulating panels, golf balls, auto body fillers, and PVC floor coverings. Their utilization is not revisited in this study. Iron oxide spheres can be utilized in heavy media separation processing such as commonly practiced by coal cleaning operations. No new technology is necessary for this application.

Cement and Concrete Applications

Introduction

A portion of the as-received ash samples from the various utilities was set aside to be used in the production of as-received concrete test specimens. The various ashes were used to replace cement in a mix designated as ASTM 35S. This designation applies to concrete with a 28 day compressive strength of 3,500 psi. The testing involved mixtures with a 8%, 20%, 30% and 40% cement replacement as well as a mix consisting solely of a Type I cement (0% replacement) as a control. Nine 6-inch diameter by 12-inch long specimens were prepared for compressive strength tests from each concrete mix. Three cylinders from each mix were tested, in accordance with standard ASTM test methods, for compressive strengths after 7 day, 28 day and 91 day curing periods.

Grade 35S concrete compression test cylinders were also produced with froth flotation beneficiated fly ash. Once again, cement replacements of 0%, 8%, 20%, 30% and 40% cement were made and testing was conducted after 7 day, 28 day and 91 day aging periods. A Type C and a Type F clean ash (NPC and AEP) were also used in mixtures to produce concrete designed to have a 28 day strength of 3,000 psi (30S) and a 28 day strength of 4,000 psi (40S). These mixes were also subjected to 7, 28 and 91 day compressive strength tests.

Materials used in the manufacture of the concrete tests specimens were selected in accordance with specifications of the Michigan Department of Transportation (MDOT), as presented in Exhibits 12 and 13.

Exhibit 12 Coarse Aggregate Grading Limits and 6A Aggregate for this Study				
Sieve Size	ASTM C 33 Requirement wt% passing size # 57	6A aggregate MDOT* specification wt% passing	6A aggregate used in this study wt% passing	6A aggregate used in this study wt% retained
1 inch	95-100	95-100	96	4
0.5 inch	25-60	30-60	36	60
No. 4 Mesh	0-10	0-8	3	
* MDOT: Michigan Department of Transportation				

The size distribution of coarse aggregate in the various mixes was 4% +1", 60% - 1"+0.5" and 36% -0.5". Materials used in the concrete mixes were stored in a controlled environment with temperatures held between 76°F and 90°F and the relative humidity between 30% and 40%.

Exhibit 13 Fine Aggregate Grading Limits and Sand Properties			
Sieve Size	ASTM C 33 Requirement wt% passing	2NS sand (MDOT* Requirement) wt% passing	2NS sand used in this study wt% passing
3/8"(9.5 mm)	100	100	100
No. 4(4.74 mm)	95-100	95-100	99.0
No. 8(2.36 mm)	80-100	65-95	83.5
No. 16(1.18 mm)	50-85	35-75	63.7
No. 30(0.6 mm)	25-60	20-55	46.2
No. 50(0.3 mm)	10-30	10-30	22.1
No. 100(0.15 mm)	2-10	0-10	9.2
Fineness modulus	2.3-3.1	2.50-3.35	2.76
Specific gravity	2.66		2.66
* MDOT: Michigan Department of Transportation			

Summaries of the composition and physical properties of the ashes used as cement replacements are presented in Appendix 8. Previously the Institute of Materials Processing (IMP) studied a dust collector ash from the Upper Peninsula Power Company (UPPCO) and a Consumers Power (FA5) Class F ash, produced using a conventional burner. Data from these samples are also presented in the Appendix.

The as-received AEP ash, from a low NO_x burner, has a very high LOI (21.7%) or percentage of unburned carbon. The only ash the IMP has worked with previously with a similar LOI was the UPPCO dust collector ash which had a LOI value of 29.8%. Comparing data from these two samples, the chemical composition of the as-received ash from AEP is very similar to that of the as-received dust collector ash, i.e. the total contents of silica, alumina and iron oxide are very close to 70%, and LOI values are higher than 20%.

After separation, the chemical compositions of cleaned AEP and UPPCO ashes are very similar. The LOI value of each decreased significantly, the sum content of silica, alumina and iron oxide is very close to 90% and the level of iron oxide did not change dramatically as a result of the removal of magnetic spheres. After froth flotation, both ashes meet the ASTM C 618 requirements. In addition, pozzolanic tests conducted by AEP on samples of as-received and clean AEP ash showed that the clean ash met ASTM-C-618, "Standard Specifications for Fly Ash or Calcined Natural Pozzolan for use as a Mineral Admixture in Portland Cement Concrete." while the as-received ash did not.

The BGE ash, from a low NO_x burner, is similar to Consumers Power Class F ash produced from coal combustion in a conventional burner. The sum content of silica, alumina and

iron oxide is nearly 87%, and LOI values are between 6% to 7.5%. The elemental composition for each ash are also nearly the same.

Concrete Testing Results

The compressive strength test data of concrete cylinder samples, with varied types and amounts of fly ash have been organized into tables. Performance, quality and workability during concrete processing, e.g. slump, air content, and density data have also been included in the tables. The effect of different fly ash on concrete properties is discussed in the following sections. It is encouraging to note that all of the 28 day strengths exceeded the basic design strength of 3500 psi.

Effect of AEP Ash on Concrete Properties

Exhibits 14 and 15 show the water requirement, workability of the fresh fly ash-cement-water mixture, and compressive strength of concrete with AEP fly ash as a partial cement replacement. The water to cementitious material ratio was designed at 0.5 for Grade 35S concrete. When the as-received ash was used to replace cement, the water to cementitious material ratio increased with the amount of cement replaced by the ash in order to obtain the desired slump value. In contrast with the as-received ash, the water to cementitious material ratio decreased with the amount of cement replaced by the cleaned ash in order to obtain the desired slump value.

The high water requirement of the as-received ash-cement-water mixture is mainly due to the high LOI content in the ash because carbon particles have a porous structure which can absorb more water. By increasing the amount of cement replaced by the ash, the number of carbon particles in a unit volume increase, therefore the water requirement increases in order to obtain the desired slump. When the LOI content is reduced by beneficiation processing, the water requirement of cleaned ash-cement-water mixture is reduced as the cleaned ash fraction increases, which improves cement workability. Differences in particle size distribution and shape between as-received and cleaned fly ash may be another factor influencing the water requirement in concrete. The high proportion of fine, smooth spherical shaped particles in the cleaned ash may improve the rheological properties of fresh concrete

The air content in fresh cement without fly ash was 7.1%. When the as-received ash was added, the air content was reduced to 2% or less. When the LOI content was reduced by the beneficiation process, the air content in the cleaned ash-cement-water mixture was an average 6.3% for grade 35S concrete.

All fresh concrete mixtures entrap a certain amount of air during mixing. It is important for there to be air in concrete to improve the workability of the fresh cement mixture, increase the impact strength of concrete, and improve the freeze/thaw behavior of the concrete. When as-

received ash was added into the mixture, carbon particles in the ash adsorbed the air entraining agent in fresh concrete because of their high specific surface area and sorption capacity, which decreased the air content in the concrete. In order to keep a equal level of entrained air in the ash-cement-water mixture as the concrete without ash, air entraining agent has to be added at a much higher dosage than usual. When the carbon content is reduced by the beneficiation process, the air content in the cleaned ash-cement-water mixture is significantly increased in all grades of concrete in comparison to the fresh concrete with as-received fly ash.

Exhibit 14 Effect of Cement Replaced by As-received AEP Fly Ash on Properties of 35S Concrete (lb per cubic yard)*				
Amount replaced	0% Mix 1	8% Mix 2	20%	30%
W/C ratio**	0.50	0.50	0.51	0.52
Cement, lb	564	517	451	395
Fly ash, lb	0	78	141	212
Water, lb	297	312	316	329
Fine Aggregate MC<0.5%	1150	1050	1014	939
Coarse Aggregate MC<1.0%	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0
AEA [#] , oz	9.90	10.70	10.90	11.10
Slump, in	3.50	3.20	2.50	2.20
Air, (%)	7.10	2.00	1.80	1.90
pci ^{##}	148.8	151.2	149.6	148.9
7 day strength, (psi) [@]	3692	4223	3357	2420
28 day strength, (psi) [@]	4676	5801	4582	3681
91 day strength, (psi) [@]	5512	6902	6201	5141
<p>* Specified design strength is 3500 psi ## Fresh unit weight (lb per cubic yard)</p> <p>** W/C ratio = water/(cement + fly ash) ratio @ Compressive strength, psi, average of 3 data</p> <p># Grace Daravair air entraining agent was used</p>				

Amount replaced	0% Mix 1	8% Mix 2	20%	30%	20% Water reducer	30% Water reducer
W/C ratio **	0.50	0.47	0.46	0.44	0.43	0.42
Cement, lb	564	517	451	395	451	395
Fly ash, lb	0	78	141	212	141	212
Water, lb	297	291	287	281	266	269
Fine Aggregate MC<0.5%	1150	1093	1098	1075	1155	1089
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845	1845
Water Reducer, oz	0	0	0	0	17.80	32.10
AEA [#] , oz	9.90	10.60	10.90	11.10	10.90	11.10
Slump, inch	3.50	3.20	3.00	3.50	3.00	3.50
Air (%)	7.10	6.50	5.50	6.90	6.50	6.00
pci ^{###}	148.8	145.4	145.8	144.2	146.6	144.8
7 day strength (psi) [@]	3692	3263	2561	2273	3103	2350
28 day strength (psi) [@]	4676	4446	4488	3681	4105	3392
91 day strength (psi) [@]	5512	6025	5442	4659	4977	4994
* ** #	Specified design strength is 3500 psi. W/C ratio = water/(cement + fly ash) ratio. Grace Daravair air entraining agent was used.		## @	Fresh unit weight (lb per cubic yard) Compressive strength, psi, average of 3 data		

Exhibit 16 shows the effects of the amount of cement replaced by fly ash and the curing period on compressive strength of Grade 35S concrete. The concrete with 8% as-received ash had higher seven-day compressive strength and the concrete with 20 and 30% as-received ash had lower seven-day compressive strengths in comparison to the concrete without fly ash. All the concrete with cleaned ash had lower seven-day compressive strength than the concrete without fly ash. The 28 day compressive strengths of both as-received and cleaned ash concrete were over 3500 psi, which satisfies the design requirement. The 91 day compressive strengths of the concrete, including both 8% and 20% as-received and 8% cleaned ash were, respectively, 6902, 6201, and 6025 psi, higher than the strength of concrete without fly ash (5512 psi). The 91 day compressive strength of the concrete with 20% cleaned ash was 5442 psi, which is nearly same as the strength of the concrete without fly ash.

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because the air content in the as-received ash concrete is low. The lower the air content, the higher the strength.

Exhibit 16 Compressive Strength Effects on Grade 35 S Concrete of Cement Replaced by As-received AEP Fly Ash

Exhibit 17 shows compressive strengths of grades 30S, 35S and 40S concrete with and without cleaned fly ash. All the grades of concrete with cleaned ash had lower seven day compressive strengths compared to the same grades of concrete without fly ash. The 28 day compressive strengths of concrete with 20% cleaned ash met the design requirement for all three grades of concrete. When 30% of the cement was replaced by cleaned ash, both the grade 35S and grade 40S concrete satisfied compressive strength specifications after 28 days. The concrete with clean ash had fast strength development from 28 to 91 days for all three grades in comparison to the concrete without fly ash. The 91 day compressive strength of grade 30S concrete including 20% cleaned ash was 4547 psi, which is higher than the strength of concrete without fly ash (4399 psi). The 91 day compressive strength of grade 35S concrete with 20% cleaned ash was 5442 psi, which is nearly the same as the strength of the concrete without fly ash (5512 psi). The 91 day compressive strength of grade 40S concrete with 20% cleaned ash was 5204 psi, which is close to the strength of the concrete without fly ash (5412 psi).

Exhibit 17 Compressive Strength Effects of Cement Replaced by Cleaned AEP Fly Ash

Effect of NPC Ash on Concrete Properties

Exhibits 18 and 19 show the water requirement, workability of fresh fly ash-cement-water mixture, and compressive strength of concrete made with NPC (Class C) fly ash as a partial cement replacement. The water to cement ratio was designed at 0.5 for Grade 35S concrete. When both as-received and cleaned ash were separately used to replace cement, the water to cementitious material ratio decreased with the amount of cement replaced by the ash in order to obtain the desired slump value. Low water requirement of both as-received and cleaned ash-cement-water mixtures is mainly due to the particle morphologies of the NPC ash. A high proportion of fine and smooth spherical particle shapes in the ash acts to improve the rheological properties of fresh concrete paste.

The air content in fresh cement paste without fly ash was 7.1%. When the as-received ash was added, the air content was reduced to 2% or less. When the carbon content was reduced by the beneficiation process, the air content in the cleaned ash-cement-water mixture had an average 3.7% for grade 35S concrete.

Exhibit 18 Effect of Cement Replaced by As-received NPC Fly Ash on Properties of 35S concrete (lb per cubic yard)*							
Amount replaced	0% Mix 1	8% Mix 2	20%	30%	40%	50%	60%
W/C ratio**	0.50	0.47	0.46	0.45	0.42	0.42	0.40
Cement, lb	564	517	451	395	339	283	226
Fly ash, lb	0	79	141	211	283	353	424
Water, lb	297	297	287	286	277	279	276
Fine Aggregate MC<0.5%	1150	1092	1063	1064	1053	1002	968
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0	0	0
AEA#, oz	9.90	10.70	10.90	11.09	11.36	11.62	11.86
Slump, in	3.50	3.50	4.00	3.50	3.25	3.75	4.00
Air, (%)	7.10	1.50	2.00	2.00	2.00	1.59	1.69
pcf###	148.8	152.8	151.8	151.6	150.9	151.4	151.2
7 day strength, (psi)@	3692	4393	4187	3657	3257	2344	1507
28 day strength, (psi)@	4676	6260	5992	5271	5277	4121	2980
91 day strength, (psi)@	5512	7304	7738	7326	7467	6302	5118
* Specified design strength is 3500 psi ** W/C ratio = water/(cement + fly ash) ratio # Grace Daravair air entraining agent was used ## Fresh unit weight (lb per cubic yard) @ Compressive strength, psi, average of 3 data							

Exhibit 19 Effect of Cement Replaced by Cleaned NPC Fly Ash on Properties of 35S Concrete (lb per cubic yard)*							
Amount replaced	0% Mix 1	8% Mix 2	20%	30%	40%	50%	60%
W/C ratio**	0.50	0.46	0.44	0.43	0.43	0.42	0.41
Cement, lb	564	517	451	395	339	283	226
Fly ash, lb	0	79	141	211	283	353	424
Water, lb	297	287	277	274	280	283	283
Fine Aggregate MC<0.5%	1150	1094	1119	1090	1049	1007	974
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0	0	0
AEA#, oz	9.90	10.70	10.90	11.09	11.36	11.61	11.86
Slump, in	3.50	3.50	3.75	3.00	3.25	2.00	2.25
Air, (%)	7.10	5.00	4.00	3.00	3.75	3.00	3.50
pcf###	148.8	147.6	149.0	150.8	147.1	143.4	146.4
7 day strength, (psi)@	3692	3557	3404	3298	2774	2044	1519
28 day strength, (psi)@	4676	4488	4929	4423	4399	3651	2684
91 day strength, (psi)@	5512	5833	6160	5624	5736	4735	4105
* Specified design strength is 3500 psi ** W/C ratio = water/(cement + fly ash) ratio # Grace Daravair air entraining agent was used ## Fresh unit weight (lb per cubic yard) @ Compressive strength, psi, average of 3 data							

Mechanical Properties of the Concrete

Exhibit 20 shows the effects of the amount of cement replaced by NPC fly ash and the curing period on the compressive strength of Grade 35S concrete. The concrete with 8% and 20% as-received ash had higher seven day compressive strengths than the concrete without fly ash. Other concrete with as-received ash had low seven day compressive strength in comparison to the concrete without fly ash. All the concrete with cleaned ash had lower seven day compressive strength than the concrete without fly ash. The concrete with 8, 20, 30, and 40% as-received ash and 20% cleaned ash had high 28 day compressive strength in comparison to the concrete without fly ash. The 28 day compressive strengths of both as-received and cleaned ash concrete, except for the sample replacing 60% of the cement, were over 3500 psi, which satisfies the design requirements. The 91 day compressive strength of the concrete with 8, 20, 30, and 40% as-received fly ash were over 7000 psi, double the design strength (3500 psi). All concrete with as-received fly ash had higher 91 day compressive strength than the concrete without fly ash, except the concrete with 60% as-received fly ash. All the concrete with cleaned ash had high 91 day compressive strength in comparison to the concrete without fly ash except the concrete with 50 and 60% cleaned fly ash.

Exhibit 20 Compressive Strength Effects on Grade 35S Concrete Replaced by NPC Fly Ash

Compared to the concrete without fly ash, the concrete with fly ash has a low early strength, except the concrete with 8% and 20% as-received ash. The concrete with fly ash has a fast strength development from 28 to 91 days, so that the concrete of both as-received and cleaned ash have higher 91 day compressive strengths than the concrete without fly ash when up to 40% of the cement is replaced by fly ash. The low early strength of concrete with fly ash is due

to less heat generated from the hydration reaction of cement when cement is partially replaced by fly ash. The high strength of concrete with fly ash after the 91 day curing period results from the low water content and high calcium content in fly ash which have cementitious as well as pozzolanic properties.

The concrete with cleaned ash has relatively low compressive strength for all ash levels and curing periods in comparison to the concrete with as-received ash. The reason for this is possibly due to the air content again. Another possible reason is the loss of fine particles and soluble components, such as CaO, during the beneficiation process, which may influence the pozzolanic properties of the cleaned ash. Further studies are needed to verify this.

Exhibit 21 shows compressive strength of grades 30S, 35S and 40S concrete with and without cleaned NPC ash. All the grades of concrete with cleaned ash had lower seven day compressive strength than the same grades of concrete without fly ash. All the 28 day compressive strengths of concrete with cleaned ash were higher than the strength of the concrete without fly ash, except the grade 35S concrete with 30% cleaned ash. For all three grades, the 28 day compressive strength of concrete with and without cleaned ash met the design requirements. The concrete with cleaned ash had a fast strength development from 28 to 91 days for all three grades in comparison to the concrete without fly ash. The 91 day compressive strength of grade 30S concrete including 20% and 30% cleaned ash were, respectively, 4977 and 5045 psi, which is higher than the strength of concrete without fly ash (4399 psi). The 91 day compressive strength of grade 35S concrete including 20% and 30% cleaned ash were, respectively, 6160 and 5624 psi which is much higher than the strength of concrete without fly ash (5512 psi). The 91 day compressive strength of grade 40S concrete including 20% and 30% cleaned ash were, respectively, 5683 and 6125 psi which is higher than the strength of concrete without fly ash (5412 psi).

Exhibit 21 Compressive Strength Effects of Cement Replacement with Cleaned NPC Fly Ash

Effect of BGE Ash on Concrete Property

The fly ash from Baltimore Gas & Electric Company is also a Class F ash. The average LOI value of as-received BGE ash is 6.2%. After separation, a cleaned BGE ash has a 1.3% LOI value. The effects of as-received and cleaned BGE ash on properties of 35S concrete are shown in Exhibits 22 and 23, respectively. The concrete containing as-received BGE ash has a much lower air content in comparison to the concrete without fly ash. The W/C ratio decreases with the increase in the amount of cement replaced by as-received BGE ash while maintaining a desired slump value. The air content of concrete containing cleaned BGE ash is also seen to be low in comparison to the concrete without fly ash, but much higher than the concrete containing as-received BGE ash. The W/C ratio decreases with an increase in the amount of cement replaced by cleaned BGE ash while maintaining a desired slump value. The 28 day compressive strengths of concrete using both as-received and cleaned BGE ash satisfy design requirements, with the exception of the concrete in which 40% of the cement was replaced by cleaned BGE ash.

Conclusions

Clean fly ash is an acceptable replacement for cement in concrete. As clean ash replaces cement, the water to cementitious materials ratio of the concrete decreases. Concrete formed with clean ash met all the requirements for air content, slump (workability), and compressive strength. Concrete using as-received ash frequently experienced difficulty meeting slump and air content requirements.

Exhibit 22 Effect of Cement Replaced by As-received BGE Fly Ash on Properties of 35S Concrete (lb per cubic yard)*					
Amount replaced	0% Mix 1	8% Mix 2	20%	30	40%
W/C ratio**	0.50	0.47	0.48	0.47	0.47
Cement, lb	564	517	451	395	338
Fly ash, lb	0	78	141	212	282
Water, lb	297	297	299	302	309
Fine Aggregate MC<0.5%	1150	1095	1078	1025	971
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0
AEA [#] , oz	9.90	10.70	10.90	11.10	11.40
Slump, in	3.50	3.50	2.20	3.00	3.00
Air, (%)	7.10	1.80	1.80	1.50	2.00
pcf ^{##}	148.8	152.2	151.5	151.3	149.4
7 day strength, (psi) [@]	3692	4482	3852	2968	2214
28 day strength, (psi) [@]	4676	6054	5383	4652	3634
91 day strength, (psi) [@]	5512	7173	6749	5899	4929
* Specified design strength is 3500 psi ** W/C ratio = water/(cement + fly ash) ratio # Grace Daravair air entraining agent was used ## Fresh unit weight (lb per cubic yard) @ Compressive strength, psi, average of 3 data					

Exhibit 23 Effect of Cement Replaced by Cleaned BGE Fly Ash on Properties of 35S Concrete (lb per cubic yard)*					
Amount replaced	0% Mix 1	8% Mix 2	20%	30	40%
W/C ratio**	0.50	0.46	0.46	0.46	0.45
Cement, lb	564	517	451	395	338
Fly ash, lb	0	78	141	212	282
Water, lb	297	291	287	293	296
Fine Aggregate MC<0.5%	1150	1110	1098	1045	1000
Coarse Aggregate MC<1.0%	1845	1845	1845	1845	1845
Water Reducer, (oz)	0	0	0	0	0
AEA [#] , oz	9.90	10.70	10.90	11.10	11.40
Slump, in	3.50	3.20	2.20	3.00	4.00
Air, (%)	7.10	5.00	4.50	3.20	4.50
pcf ^{##}	148.8	147.4	148.3	147.8	145.1
7 day strength, (psi) [@]	3692	3322	2821	2468	1814
28 day strength, (psi) [@]	4676	4588	4158	3698	2921
91 day strength, (psi) [@]	5512	5453	4988	4005	4682
* Specified design strength is 3500 psi ** W/C ratio = water/(cement + fly ash) ratio # Grace Daravair air entraining agent was used ## Fresh unit weight (lb per cubic yard) @ Compressive strength, psi, average of 3 data					

Concrete Block/Brick

Concrete blocks and bricks were formed at Alpena Community College in Alpena, Michigan, March 17-20, 1996. The college operates a concrete block forming laboratory in conjunction with Besser Company, one of the world's largest manufacturers of concrete block making equipment. A test plan was developed and discussions were held with the college laboratory personnel regarding the manufacturing process and the effects of the main process parameters on properties, and quality control. A series of experiments, using three different sources of both as-received and cleaned fly ash, was conducted to determine the influence of ash type and the beneficiation process on block quality. Exhibit 24 describes the test plan for block manufacture. A test plan for concrete paving bricks was also developed and is summarized in Exhibit 25. Each test plan included block and bricks formed without fly ash.

Computer controlled Besser forming equipment was used in the block and brick work. The main process variables influencing product quality are blending time, water to cement ratio, feed time, and finish time. These were controlled during the testing to ensure the production of quality products. After manufacturing, physical and mechanical properties of the block and brick were tested. Physical property measurements included density, moisture content, absorption, and dry shrinkage. Mechanical property tests included 1, 7, 14, and 28 day gross compressive strength and impact strength.

Exhibit 24 Block Manufacture Test Plan		
Batch	Fly Ash Type	Cement replaced by fly ash (weight %)
1	As-received Class F	20
2	As-received Class C	20
3	As-received Class F/C	20
4	Clean Class F	15
5	Clean Class C	15
6	Clean Class F/C	15
7	Clean Class F	20
8	Clean Class C	20
9	Clean Class F/C	20
10	Clean Class F	30
11	Clean Class C	30
12	Clean Class F/C	30
13	No fly ash	0
<i>Notes:</i> 1. Normal weight blocks (8x8x6 with 2 hollow cores) were made in this experiment. 2. Each batch will manufacture 68 to 72 blocks. 3. After the blocks are fabricated, they were low-pressure steam cured at 165°F for 12 hours. 4. The cured blocks were stored at room temperature and tested following ASTM standards.		

Exhibit 25 Test Plan for Brick Manufacture		
Batch	Fly Ash Type	Amount of cement replaced by fly ash (weight)
1	As-received Class F/C	20
2	Clean Class F/C	20
3	No fly ash	0

Notes:

1. Normal weight bricks are to be made in this experiment.
2. Each batch will manufacture 68 to 72 bricks.
3. After the bricks are fabricated, they will be low-pressure-steam cured at 165° F for 12 hours.
4. The cured bricks will be stored at room temperature and tested following ASTM standards.

AEP fly ash was used to replace cement in concrete block manufacturing. Test results are presented in Exhibits 26 and 27. All blocks made with fly ash had lower compressive strengths than the control blocks, regardless of the length of the curing period. All the concrete with cleaned ash had a lower one day compressive strength than the concrete with 20% as-received ash. The blocks with 15% and 20% cleaned ash had higher fourteen day compressive strengths than the concrete with 20% as-received ash. The 28 day compressive strengths of both as-received and cleaned ash concrete met design requirement.

Exhibit 26 Compressive Strength of Concrete Block (AEP Class F Fly Ash)

Exhibit 27 Physical and Mechanical Properties of Concrete Block with AEP Fly Ash						
Test period	Block properties	Block without fly ash	Block with 20% as-received ash	Cleaned ash content in block		
				15%	20%	30%
1 day	Density (pcf ^a)	138.2	133.0	133.0	134.3	133.9
	Moisture content (%)	37.8	23.8	23.8	24.3	16.8
	Absorption (pcf)	7.5	7.9	7.9	7.7	7.5
	Compressive strength (psi)	2260	1750	1870	1380	1320
7 day	Density (pcf)	138.2	134.5	133.0	134.3	133.9
	Moisture content (%)	37.8	28.1	26.8	24.3	24.6
	Absorption (pcf)	7.5	8.2	7.9	7.7	7.5
	Compressive strength (psi)	3120	2130	2860	2320	1930
14 day	Density (pcf)	138.2	134.3	133.0	134.5	133.9
	Moisture content (%)	37.8	24.3	23.8	28.1	24.6
	Absorption (pcf)	7.5	7.7	7.9	8.2	7.5
	Compressive strength (psi)	3310	2400	2950	2520	2280
28 day	Density (pcf)	138.2	131.0	133.0	134.3	133.9
	Moisture content (%)	37.8	21.4	26.8	24.3	24.6
	Absorption (pcf)	7.5	9.1	7.9	7.7	7.5
	Compressive strength (psi)	3290	2270	3320	2320	2000
<i>Note: a) pcf is pound per cubic foot</i>						

Exhibits 28 and 29 show the density, moisture content, absorption, and compressive strength of concrete blocks made with and without NPC as-received and cleaned fly ash at various curing periods. The moisture content in blocks without fly ash averaged 37.8% for all curing periods, which is higher than the blocks with as-received or cleaned ash. The absorption in blocks without fly ash averaged 7.5% for all curing periods, which is lower than the blocks with as-received or cleaned ash. This is probably related to the cement ratio used to make the blocks; more water is required to hydrate the additional cement as the amount of cement in the concrete mix increases. Higher cement content in the blocks (without ash) requires more water for the hydration reaction, which results in high moisture content. After curing, the cement in the blocks resists absorbing moisture from the atmosphere.

Exhibit 28 Physical and Mechanical Properties of Concrete Block with NPC Fly Ash						
Test period	Block properties	Block without fly ash	Block with 20% as-received ash	Cleaned ash content in block		
				15%	20%	30%
1 day	Density (pcf ^a)	138.2	129.0	133.0	132.3	132.3
	Moisture content (%)	37.8	21.4	23.8	21.5	21.5
	Absorption (pcf)	7.5	9.0	7.9	9.1	9.1
	Compressive strength (psi)	2260	1420	1870	1220	1050
7 day	Density (pcf)	138.2	134.5	133.0	136.0	138.4
	Moisture content (%)	37.8	13.2	26.8	26.0	21.3
	Absorption (pcf)	7.5	8.2	7.9	8.2	9.6
	Compressive strength (psi)	3120	2450	2860	2380	2190
14 day	Density (pcf)	138.2	133.2	133.0	136.0	132.3
	Moisture content (%)	37.8	34.4	23.8	26.0	21.5
	Absorption (pcf)	7.5	8.7	7.9	8.2	9.1
	Compressive strength (psi)	3310	2520	2950	2720	2240
28 day	Density (pcf)	138.2	134.8	133.0	136.0	135.4
	Moisture content (%)	37.8	28.1	26.8	26.0	25.3
	Absorption (pcf)	7.5	8.2	7.9	8.2	7.2
	Compressive strength (psi)	3290	2420	3320	2830	2350

Note: a) pcf is pounds per cubic yard

Exhibit 29 Compressive Strength of Concrete Block (NPC Class C Fly Ash)

Plastic Filler Applications

Introduction

A potential application for fly ash, other than as a substitute for cement, is as a plastics resin filler. Mineral fillers are widely used in plastic products to improve performance and reduce the costs. The minerals commonly used for plastic fillers include calcium carbonate, kaolin, aluminum trihydrate, talc and titanium dioxide. Calcium carbonate accounts for about 70% of the fillers used. Fly ash can be classified as a mineral based on its chemistry and physical nature. The characteristics of fly ash are very close to a number of commercial fillers. Previous studies have indicated that the use of fly ash as a plastic filler has shown promising results.[10-12] However, the particle size and brightness of fly ash are still less desirable than those of a typical commercial filler. The objective of this research is to further process the clean fly ash by separating the finest fraction and improving its brightness while evaluating its performance as a plastic filler.

Most commercial plastic fillers have a mean diameter of only a few microns. The average particle size of the clean AEP ash is about 30 microns with about 15% having a mean diameter of less than 5 microns. Based on the clean ash size distribution and commercial filler specification, clean ash with a maximum particle size of 5 microns seems to be an appropriate choice to satisfy basic plastic filler requirements. Both a hydrocyclone and an air classification system offer a potential means for the separating of fly ash into two fractions using 5 microns as the cut. In this study an air classifier was used for the separation.

The approach adopted in this study to improve brightness was to control the precipitation of TiO_2 , CaCO_3 or ZnO onto the clean ash surface. The evaluation of the fine clean ash coated with a coupling agent as a plastic filler was conducted by comparing it to three polymers, polypropylene, low density polyethylene and high density polyethylene, compounded with a commercial CaCO_3 filler under the same conditions. At the end of the study, a plastic company tested the resulting polymers, compounded with clean ash, to produce commercial auto parts.

Froth flotation beneficiated fly ash from AEP fly ash from low NO_x burners was used to evaluate its effectiveness as a plastics filler. The clean fly ash had a mean particle size of about 30 microns which is coarser than a typical commercial fillers used by the plastics industry. Air classification was used to separate the clean fly ash into coarse and fine fractions. The resulting fine fraction had a mean particle size of 4.13 microns and accounted for 16.7 wt % of the total clean ash. The brightness of the clean ash was also less than that of typical commercial fillers and efforts to improve the brightness proved unsuccessful. The clean ash was coated with a silane coupling agent before being added to polypropylene, low density polyethylene, and high density polyethylene at various levels. Injection molding was used to make tensile test specimens from the various polymer/filler mixtures. For comparison, resins with a commercial CaCO_3 filler added were also tested under the same conditions. In most cases the mechanical properties of comparable specimens were shown to be equivalent.

Experimental Procedures

Classification An Acucut air classifier was used for the air classification task. The classification tests initiated with the runs being conducted under different operating parameters to determine the optimum conditions for the cut desired. After each test, a Leeds & Northrup Microtrac was used to determine the resulting fractions. Twelve test runs were required to find the most favorable operating conditions and the parameters were used to produce more than 3 kg of clean AEP ash with a particle size of less than 5 microns.

Characterization The most important characteristics for a mineral product to be considered as a plastic filler are mean particle size, size distribution, shape, oil absorption, loose density, tap density, brightness, pH, and composition. The 5 micron AEP fly ash fraction was characterized according to these properties. The particle size and size distribution was analyzed using a Leeds & Northrup Microtrac analyzer. The particle shape was established using a JEOL JSM 820 scanning electron microscope. The loose density was measured by charging the ash into a 100 ml graduated cylinder, weighing the 100 ml of ash, and dividing the weight by the 100 ml. The tap density was measured by charging ash into a 100 ml graduated cylinder, taping the cylinder 100 times on a Stave 2003 stamp volumeter, measuring the weight and volume, and again simply dividing the weight by the volume. Oil absorption was determined by following ASTM standard D281. Brightness was determined using a ZEISS photoelectric reflectance photometer with a swing-in brightness standard at brightness of 95.9%. The pH was measured following ASTM standard D4972.

Brightness Improvement Test The object of the fly ash brightness work was to produce a precipitated TiO_2 , CaCO_3 or ZnO coating on the surface of fly ash particles. The principle involved was to control the reaction between materials so that the resulting product would only nucleate and grow on fly ash surface. The TiO_2 , CaCO_3 and ZnO precipitations were produced according to the following reactions:

A slurry of 5% clean ash and two reactant solutions with low concentration but proper ratios based on the above reactions were prepared. The two reactant solutions were charged into 250 ml burets and very slowly fed into a beaker containing the fly ash slurry and being stirred.

Polymers Soo Plastics in Sault Ste. Marie, Michigan was retained to evaluate commercial application of beneficiated fly ash filled resins. The company donated polypropylene, low density polyethylene, and high density polyethylene as normally used in their production process. The polymers were polypropylene homopolymer T-3922 nat., Escorene LL 6407.67 nat. linear low density polyethylene, and HXM 50100 nat. high density polyethylene. These polymers were

produced by Fina Oil & Chemical Company, Exxon Chemical Americas, and Phillips Petroleum, respectively.

Filler Surface Treatment The fly ash filler was coated with a silane coupling agent to promote bonding between the filler and polymer matrix. Silane is a series of products formulated for different filler and polymer systems and is one of the most commonly used coupling agent. After consulting with the Dow Corning Corporation, a silane manufacturer, their Z-6032 was selected for testing. The properties of this coupling agent are outlined in Exhibit 30. The fine ash was coated with the silane, using the procedure given in Exhibit 31.

Exhibit 30 Typical Properties of Dow Corning Z-6032 Silane	
Functionality	vinylbenzyl-amine-methoxy
Percent Solids	40
Solvent	methanol
Specific Gravity at 25°C	0.900
Flash Point, closed cup, °C	13
Viscosity, at 25°C, cSt	2
Suitable diluents	alcohols, water
Shelf life (from date of shipment)	6 months

Exhibit 31 Silane Coating Procedure	
Step	Activity
1	silane amount = 0.5 weight percent of ash
2	silane dilution: add 100 times by weight distilled water
3	Mix the silane solution with ash for 10 minutes
4	Oven dry the slurry
5	Crush the coated ash powder through a 100 mesh screen

Commercial Calcium Carbonate Filler A commercial CaCO_3 filler commonly used with polymers, Gama-Sperse CS-11, was acquired from the Georgia Marble Company. This filler was precoated with 1% stearate by the manufacturer and no additional coupling agents were added to the calcium carbonate in this study.

Polymer and Filler Mixing Polypropylene, low density polyethylene, and high density polyethylene were compounded with the fine ash fraction and with the commercial calcium carbonate filler. Each polymer was compounded with ash and calcium carbonate at concentrations of 0, 10, 20, 40 and 80 parts per hundred parts of resin (phr). Each of the batches was mixed for 30 minutes in a Brabender Plasti-Corder torque-rheometer at 50 RPM. The mixing temperatures were 250°C, 190°C and 200°C for polypropylene, low density polyethylene, and high density polyethylene, respectively.

Injection Molding Test Injection molding is one of the primary forming processes used by the plastic industry to produce various products. In this research, an Arburg 221-75-350 injection molding machine with a four-cavity standard tensile specimen mold was used for forming test specimens. The machine is capable of providing 35 tons of clamping force and 7.5 tons of injection force. The mold cavities are water jacketed to control mold temperature. The water temperature was controlled by a Model TDW-INX conditioner, manufactured by Application Engineering Corporation. If a polymer and filler mixture proved to be injection moldable, ten tensile specimens were produced from each batch for mechanical testing.

Mechanical Testing The modules of elasticity, elongation, yield and ultimate strengths of the specimens produced by injection molding were determined by following ASTM standard D638 with an Instron testing system. If the elongation of a specimen was less than 40%, the elongation was measured automatically by an extensometer. If the elongation of a specimen was greater than 40%, the elongation was measured manually.

Fracture Surface Examinations Fracture surfaces of tensile test specimens were made with the assistance of a scanning electron microscope. Particular attention was paid to the bonding between the polymers and the fillers.

Demonstration of Commercial Manufacturing Arrangements were made with a local plastics firm to injection mold various commercial products using the compounds discussed above. The compounds were granulated to a size that would flow freely from the feed hopper through the feed chute and into the barrel of a commercial injection molding machine. The resulting three compounds were used to produce two different automotive parts, a trim clip being used by Chrysler and a component to support an under the hood wiring harness used by General Motors. The trim clip was chosen as a result of the symmetrical cavity layout and because the major surfaces were parallel and perpendicular to the runner. In addition the GM part contained large radii and smooth surfaces that would provide a good indication of the surface quality that could be expected from molding compounds containing fly ash.

Results and Discussion

Classification Exhibit 32 presents a typical air classification result. The yield is 6.7% yield with a mean particle size of 4.13 microns. The operating parameters associated with this test were used to produce more than 3 kg of fine ash. Exhibit 33 shows two particle size distribution analyses of the samples taken from the bottom and top of the 3 kg batch. The two analyses results are very close and show a relatively narrower size distribution of the fine ash. The mean particle sizes of the bottom and top samples are 3.96 and 4.19 microns respectively.

Exhibit 32 Air Classification Results				
	Coarse Fraction		Fine Fraction	
Test No.	Mean Size (Microns)	Yield %	Mean Size (Microns)	Yield %
4	28.11	95.4	3.46	4.6
5	35.12	94.6	2.95	5.4
6	33.10	92.2	3.13	7.8
7	39.59	86.1	4.25	13.9
8	36.20	97.9	2.61	2.1
9	29.04	99.3	2.71	0.7
10	38.27	83.3	4.13	16.7
11	37.69	82.3	4.65	17.7
12	37.33	88.9	21.18	11.1

Exhibit 33 Particle Size Distribution of Fine AEP Fly Ash				
Particle Size Microns	Bottom Sample		Top Sample	
	Cumulative, %	Volume, %	Cumulative, %	Volume, %
22	100.0	0.0	100.0	0.0
16	100.0	0.8	100.0	1.6
11	99.2	5.1	98.4	6.1
7.8	94.2	13.8	92.4	15.3
5.5	80.4	21.0	77.1	22.1
3.9	59.4	24.0	55.0	22.3
2.8	35.4	19.9	32.7	18.2
1.9	15.4	8.3	14.5	7.8
1.4	7.1	5.2	6.7	4.9
0.9	1.9	1.9	1.8	1.8

Characterization The particle shape associated with the fine fraction of the clean AEP ash is shown in Exhibit 34. The particles are spherical except for a few irregular shaped impurities. The mean particle size, loose and tap densities, brightness, pH, and oil absorption of the ash are presented in Exhibit 35. Exhibit 36 shows the characterization of a commercial calcium carbonate filler and a commercial alumino-silicate filler. Exhibit 37 gives the particle size distribution information of the two commercial fillers. Exhibit 38 shows the alumino-silicate filler's shape.

Exhibit 34 Particle Shape of Fine Clean AEP Ash

In comparison with the commercial fillers, the fly ash filler has similar mean particle sizes, narrower particle size distribution, a reduced variation in the loose and tap densities, and oil absorption similar to that of alumino-silicate filler. The pH of the fly ash filler falls between the two commercial fillers. The major differences between the commercial and fly ash fillers are the lower brightness and spherical shape of the fly ash filler. While the lower brightness of the ash may reduce its applications, there are many applications where color consistency is more important than the color itself.

Exhibit 35 Characteristics of Fine Clean AEP Fly Ash as a Plastic Filler	
Properties	AEP-C-4M
Mean particle size, microns	4.13
Loose density, g/cc	0.804
Tap density, g/cc	0.874
Brightness	24.2
pH	6.6
Oil absorption	30

Exhibit 36 Characteristics of Commercial Calcium Carbonate and Alumino-Silicate Fillers		
Properties	Calcium carbonate Gama-Sperse CS-11	Alumino-silicate ASP 400P
Mean particle size, microns	3.0	4.8
Loose density, g/cc	0.56	0.38
Tap density, g/cc	n/a	0.72
Brightness	94	79-82
pH	9.5	3.5-5.0
Oil absorption	16	30-35

Exhibit 37 Particle Size Distributions of Calcium Carbonate and Alumino-Silicate Fillers				
Particle Size Microns	Gama-Sperse CS-11		ASP 400P	
	Cumulative, %	Volume, %	Cumulative, %	Volume, %
22	100.0	0.0	100.0	6
16	100.0	4.5	94	7
11	95.5	9.5	87	10
7.8	86.0	13.5	77	21
5.5	72.5	15.0	56	14
3.9	57.5	17.5	42	12
2.8	40.0	12.0	30	10
1.9	28.0	6.0	20	6
1.4	22.0	7.5	14	7
0.9	14.5	14.5	7	7

Exhibit 38 Particle Shape of Commercial Alumino-silicate Filler

Brightness Improvement Test It has been established by our studies that TiO_2 and CaCO_3 crystals formed by very slow precipitation are transparent and tend not to nucleate on the fly ash surfaces. Exhibit 39 is an example of the CaCO_3 precipitation coating. The cubic particles are CaCO_3 crystals and the spheres are fly ash. Coating tests with both TiO_2 and CaCO_3 were not successful in improving the brightness of fly ash. Trials with precipitated $\text{ZnO}/\text{ZnO}(\text{OH})_2$ also were not successful in improving brightness even though the SEM image (Exhibit 40) indicates fly ash particles coated the entire fly ash surfaces.

Exhibit 39 CaCO_3 Precipitation on Fly Ash Surfaces

The precipitation of pure $\text{ZnO}/\text{Zn}(\text{OH})_2$ without fly ash as nuclei was also conducted and resulted in a very white surface. One possible reason for the large brightness difference could be contamination by the leaching of fly ash impurities and their interference with the $\text{ZnO}/\text{Zn}(\text{OH})_2$ nucleation. Another possible reason could be that the coating was too thin. As an attempt to identify the problem a multilayer coating was tried. When this was done the resulting fly ash particles had grown from an initial size of about 20 microns to a few hundred microns. A comparison test was also made using a steel stirrer and a polymer coated magnetic bar to mix the precipitating ZnO . The ZnO precipitations using a magnetic bar as a stirrer were brighter than when using a steel stirrer. This indicated contamination of iron from the steel was present.

Exhibit 40 $\text{ZnO}/\text{Zn}(\text{OH})_2$ Precipitation on Fly Ash Surfaces

A leaching test, adding different amounts of HCl in fly ash slurry resulted in yellowish solutions. ICP analyses of these solutions revealed that many elements are leachable from fly ash when it is slurred in an acid solution. Exhibit 40 shows the ICP analysis results. The pH of the coating slurry is about 6. We also found that a longer settling time resulted in a darker appearance. These results indicate that the elements being leached from fly ash during a coating test caused contamination, resulting in an off-white color.

Exhibit 41 Leaching Test Results			
Element	Leaching Solution Analysis, ppm		
	X1FLY	X2FLY	X3FLY
Si	66.39	65.2	66.9
Mg	23.74	28.23	25.44
Mn	0.7236	0.7432	0.7566
Pb	1.206	1.201	1.233
Ba	8.077	8.338	8.841
K	32.79	35.05	37.04
Na	6.458	6.831	7.83
Ni	0.7788	0.7787	0.896
Al	273.9	285.6	288.6
Ca	88.54	95.32	89.07
Fe	84.79	91.86	86.51
Zn	3.875	3.867	2.046
Cu	1.419	1.522	1.45
P	10.3	10.27	10.63

Injection Molding Tests The addition of a filler to a polymer increases the viscosity of the resulting compound when it is melted. This increase in viscosity decreases the polymers moldability. When filler is added beyond a certain level, the compound may become so viscous that it cannot be injection-molded.

In some applications, higher filler loading is required to achieve the targeted properties. In turn it would be desirable to have a filler that would be capable of higher loading for wider applications. In this study, compounds were injection-molded with temperature and pressure purposely lowered. If the polymer compounds could not be injected, the injection pressure was gradually increased until the compound could be injected fully into the mold. If the maximum pressure could not inject the compound, the mold temperature was increased gradually without surpassing suggested injection upper temperature limit for the polymer. Exhibits 42 - 44 list the injection molding parameters for the polypropylene, low density polyethylene, and high density polyethylene compounds as well as the various concentrations of fine AEP ash and the commercial calcium carbonate fillers used.

Filler levels, using either AEP ash or calcium carbonate, at or below 80 phr in polypropylene did not result in any difficulties in the injection molding of the compounds. Each were injection-molded under the conditions listed in Exhibit 42. The addition of fillers in the low density polyethylene decreased the moldability of the compound more significantly. The injection pressure had to be increased to overcome the increase in viscosity as the filler content increased. The low density polyethylene with 40 phr fly ash required 700 psi injection pressure, while the same polymer with 40 phr calcium carbonate filler required 900 psi pressure, as shown in Exhibit 43. When the loading level increased to 80 phr, the low density polyethylene with fly ash was still moldable but the same polymer with calcium carbonate filler was not, even when the injection pressure was increased to the maximum 2200 psi.

The high density polyethylene (Exhibit 44) proved more difficult to inject because of its higher viscosity. The injection pressure had to be greater than 1200 psi in order to fully fill the mold cavity, even with the pure polymer. The addition of fly ash filler at levels below or equal to 40 phr did not cause any injection problems, however the addition of calcium carbonate filler in the amount of 40 phr introduced a significant increase in viscosity. The injection pressure had to be adjusted to the maximum of 2200 psi, the mold temperature raised from 100°F to 140°F, and the injection temperatures increased to the highest suggested temperatures for this polymer. Even so it was not possible to fully fill the mold cavity.

The injection molding tests indicated that polypropylene, low and high density polyethylene compounded with fine AEP ash have similar or better moldability than when compounded with a commercial calcium carbonate filler.

Exhibit 42 Injection Molding Test of Polypropylene with Fillers									
Fillers	Filler Content phr	Zone I Temp. °C	Zone II Temp. °C	Zone III Temp. °C	Zone IV Temp. °C	Injection Velocity Dial*	Injection Pressure psi	Holding Pressure psi	Mold Temp. °F
None	0	210	220	210	200	5.0	400	100	100
Fly Ash CaCO ₃	10	210	220	210	200	5.0	400	100	100
	10	210	220	210	200	5.0	400	100	100
Fly Ash CaCO ₃	20	210	220	210	200	5.0	400	100	100
	20	210	220	210	200	5.0	400	100	100
Fly Ash CaCO ₃	40	210	220	210	200	5.0	400	100	100
	40	210	220	210	200	5.0	400	100	100
Fly Ash CaCO ₃	80	210	220	210	200	5.0	400	100	100
	80	210	220	210	200	5.0	400	100	100
* Dial 5.0 is the maximum injection velocity of the machine									

Exhibit 43 Injection Molding Test of Low Density Polyethylene with Fillers									
Fillers	Filler Content phr	Zone I Temp. °C	Zone II Temp. °C	Zone III Temp. °C	Zone IV Temp. °C	Injection Velocity Dial*	Injection Pressure psi	Holding Pressure psi	Mold Temp. °F
None	0	210	220	210	200	5.0	500	100	100
Fly Ash CaCO ₃	10	210	220	210	200	5.0	500	100	100
	10	210	220	210	200	5.0	500	100	100
Fly Ash CaCO ₃	20	220	230	220	210	5.0	700	100	100
	20	220	230	220	210	5.0	700	100	100
Fly Ash CaCO ₃	40	220	230	220	210	5.0	700	100	100
	40	220	230	220	210	5.0	900	100	100
Fly Ash CaCO ₃ *	80	220	230	220	210	5.0	900	150	100
	80	240	250	240	230	5.0	2200	150	120
* This material could not be injected even at the maximum pressure of 2200 psi.									

Exhibit 44 Injection Molding Test of High Density Polyethylene with Fillers									
Fillers	Filler Content phr	Zone I Temp. °C	Zone II Temp. °C	Zone III Temp. °C	Zone IV Temp. °C	Injection Velocity Dial*	Injection Pressure psi	Holding Pressure psi	Mold Temp. °F
None	0	260	260	250	250	5.0	1200	100	100
Fly Ash CaCO ₃	10	260	260	250	250	5.0	1200	100	100
	10	260	260	250	250	5.0	1200	100	100
Fly Ash CaCO ₃	20	260	260	250	250	5.0	1200	100	100
	20	260	260	250	250	5.0	1200	100	100
Fly Ash CaCO ₃ *	40	260	260	250	250	5.0	1200	100	100
	40	290	290	270	270	5.0	2200	100	140
* This material could not be injected even at the maximum pressure of 2200 psi.									

Mechanical Properties The ultimate tensile strength, yield strength, elongation and Young's modules are the most important mechanical properties for polymer materials. Filler content, filler particle size, size distribution, shape, mixing quality, and bonding between filler and polymer matrix all affect the mechanical properties.

As a rule, higher filler content leads to higher yield strength and an increase in the Young's modules while a lower elongation would be expected because the filler particles restrict deformation of the polymers. The fillers also affect the ultimate tensile strength (UTS) in two ways. First, the filler particles cause stress concentration and initiate cracks, lowering UTS.

Second, if the particles have the proper shape and a strong bonding between the particles and the polymer matrix, the particles may serve to reinforce polymer, resulting in higher UTS. With regard to size, the larger particles usually reduce the UTS and elongation.

Exhibit 45 presents the mechanical properties of polypropylene filled with fly ash and calcium carbonate. This Exhibit indicates that the yield strength and Young's modules increase and UTS and elongation decreases as the filler content increases, except when calcium carbonate content is over 40 phr. At this level the calcium carbonate filler begins to decrease the yield strength as well as the Young's modules. With lower calcium carbonate contents of 10 and 20 phr, the polypropylene compound shows higher UTS than those of the polymers with fly ash filler. When the calcium carbonate content exceeds 40 phr, the UTS of the compound is lower than that of the compounds with ash as the filler. The yield strength and Young's modules of polypropylene with an ash filler are higher than those of polypropylene with calcium carbonate filler, but the elongation is lower than that of the counterpart. In general, ash filler can replace calcium carbonate filler to achieve the equivalent mechanical properties when the filler content is less than or equal to 20 phr.

Exhibit 46 shows the results of the mechanical tests for the low density polyethylene with ash and calcium carbonate fillers. The low density polyethylene with ash filler have better mechanical properties than those of the same polymer with calcium carbonate filler. This superiority is more obvious at the higher loading level of 40 phr.

Exhibit 47 gives the mechanical properties for the high density polyethylene with ash and calcium carbonate fillers. The noticeable phenomenon is that the UTS increases when filler content reaches 40 phr for the polymer with ash filler. This indicates that the ash filler may reinforce the polymer matrix. Over all, the high density polyethylene with an ash filler has better strengths and Young's modules than those of the polymer with calcium carbonate filler, but the elongation is not as good as its counterpart.

Exhibit 45 Mechanical Properties of Polypropylene with Fillers					
Fillers	Filler Content phr	Ultimate Tensile Strength, psi	Yield Strength psi	Elongation %	Young's Modules, ksi
None	0	6666	1728	650	185
Fly Ash	10	4724	2199	630	189
CaCO ₃	10	5024	1880	650	164
Fly Ash	20	4378	2340	467	211
CaCO ₃	20	4928	2114	600	178
Fly Ash	40	4267	2416	32	237
CaCO ₃	40	3850	1738	367	125
Fly Ash	80	3953	2474	1.3	314
CaCO ₃	80	2900	1480	41.7	217

Exhibit 46 Mechanical Properties of Filled Low Density Polyethylene					
Fillers	Filler Content phr	Ultimate Tensile Strength, psi	Yield Strength psi	Elongation %	Young's Modules, ksi
None	0	3336	485	467	27.5
Fly Ash CaCO ₃	10	3463	557	467	36.0
	10	3255	545	467	33.4
Fly Ash CaCO ₃	20	2635	560	462	39.4
	20	2563	573	483	33.6
Fly Ash CaCO ₃	40	2449	738	450	47.3
	40	1905	574	442	33.6
Fly Ash CaCO ₃	80 80	2377 -	888 -	46.6 -	90.5 -

Exhibit 47 Mechanical Properties of High Density Polyethylene with Fillers					
Fillers	Filler Content phr	Ultimate Tensile Strength, psi	Yield Strength psi	Elongation %	Young's Modules, ksi
None	0	5040	1016	60	79.4
Fly Ash CaCO ₃	10	4843	1192	45	73.2
	10	3807	940	83	45.2
Fly Ash CaCO ₃	20	4823	1160	50	81.6
	20	3698	1089	84	56.6
Fly Ash CaCO ₃	40 40	5219 -	1279 -	28 -	96.4 -

Fracture Surface Examinations SEM images indicate that, in general, the fillers had been homogeneously mixed with the polymers. Photomicrographs in Appendix 9 show the fracture surfaces of the polypropylene, low density polyethylene and high density polyethylene with 40 phr of ash filler and calcium carbonate filler. It appears that fly ash, along with the silane coupling agent, has better bonding with the three polymers than when calcium carbonate is used as the filler.

Demonstration of Commercial Manufacturing A VanDorn, Model #75-RS-4F, injection machine was used to process the ash filled compounds. Since VanDorn is a large and well established producer of injection molding machines, the use of this machine provided a very good representation of the typical injection molding machine in use by industry. Injection of the trim clip was carried out first because it was a much smaller component and clean-up would not have been difficult if the experimental materials had proved difficult to inject. Yet all went smoothly during the production trial, material flowed well, cavities filled uniformly, lines were well defined and parting of the product from the mold was realized without the addition of a release agent. The operators, as well as the owner of the business, said they could not distinguish between the

operation of the machine using the experimental compounds and the commercial materials typically used to produce the trim clips.

Exhibit 48 shows the parts produced from one of the fly ash filled polymers. The injection of the GM wiring harness support also proceeded smoothly. Although the shape was of a nature that considerably more resistance was encountered during molding, the material readily filled the cavities. Adjustments were made to the injection pressure, holding pressure and back pressure however, the new settings were typical of what would be expected given the nature of the die and not a result of the variation in the compound being injected. Exhibit 49 presents the GM wiring harness supports produced from one of the ash filled polymers.

Exhibit 48 Trim Clips Produced from Ash Filled Polymer

Exhibit 49 GM Wiring Harness Support Produced from Ash Filled Polymer

With the successful mechanical test results in hand, the prime industrial concern regarding the acceptability of fly ash filled polymers became the surface quality of the finished products. The parts containing 10 phr displayed very smooth somewhat glossy surfaces. Injection molding of compounds containing 20 phr produced parts that had a somewhat opaque finish, yet the surface was still very smooth. The molded parts produced from compounds containing 40 phr displayed an uneven surface that was dull in nature and revealed flow patterns. The equipment operator was quick to point out that this type of surface appearance was common when compounds with high amount of fillers were molded and that the physical properties were not significantly affected as a result.

Overall the injection molding of ash filled compounds went very smoothly. No major problems were encountered. The resulting production parts indicated that a quality finish could be expected when using these materials to produce commercial products.

Conclusions

AEP as-received low NO_x ash can be processed to produce fine clean powders with the characters suitable for plastic filler application. The particle size distribution is narrower than that of two comparable commercial fillers. Fly ash brightness is much lower than that of commercial calcium carbonate filler and alumino-silicate filler and would have to be taken into consideration prior to its commercial use. The unique spherical shape of fly ash makes allows molding to be accomplished at lower temperatures and pressures. These less severe operating conditions result in reduces energy costs of production and reduces equipment wear in comparison to the use of conventional fillers.

Polypropylene, low density and high density polyethylene compounds with fine clean ash filler have equivalent or better moldability when compared to a commercial calcium carbonate filler. In general, polypropylene and high density polyethylene with fine clean ash filler show equivalent or better strengths and Young's modules, but the elongation is not as good as that experienced from the use of a commercial calcium carbonate filler. The mechanical properties of low density polyethylene with the fine clean ash filler were superior to moldings made with the same polymer and calcium carbonate filler, regardless of loading level.

Physical examination indicated there was very good bonding between beneficiated fly ash particles matrices of low density and high density polyethylene, when the ash was coated with Dow Corning Z-6032 silane bonding agent.

Polymers made with ash filler were demonstrated as being capable of being injection molded into commercial automotive parts with no deterioration of moldability, dimension accuracy and surface quality in comparison with the commercially filled polymer compounds.

Activated Carbon

Introduction

Activated carbon is a solid that has an extremely large internal surface area and pore volume. These characteristics and the affinity of carbon for a wide range of organic and inorganic materials are responsible for the use of activated carbon in production processes and environmental situations. It has traditionally been used to purify chemicals, pharmaceuticals and foodstuffs, and to treat drinking water. More recently it has found uses in pollution control and the production of synthetic products. The total surface area of commercial activated carbons ranges from 450 square meters per gram to 1,800 square meters per gram as measured by the Brunauer-Emmett-Teller (BET) method.

Although surface area and adsorption are interrelated, surface area alone is not always a satisfactory measure of the adsorption capacity of a specific carbon. The distribution of pore volume as a function of pore size is also important since different agents to be adsorbed are of varying sizes and large molecules are not easily adsorbed if pore size is too small. As a point of reference, odor causing impurities tend to be smaller than color-forming impurities.

Activated carbons are used either as liquid-phase adsorbents to decolorize or purify liquids, or as gas-phase adsorbents for solvent vapor recovery and gas separation. The main difference between the two uses is that activated carbon for vapor adsorption usually have a high volume of micro pores of less than 32 Å. The pore size of liquid-phase adsorbents ranges from 1,000 to 2,000 Å. Liquid-phase carbons are used in the powdered and granular form. Powdered carbons are mixed with the liquid to be treated and removed by filtration or settling. Virtually all vapor phase systems use granular carbon.

Even though both granular and powdered carbon can be regenerated, the granulated form is more commonly used in high carbon usage applications because fully developed systems are available for its regeneration. On the other hand, powdered carbon is used when adsorption requirements are very specific, such as removing undesired color from foods without adsorbing chemicals affecting flavor.

Virtually any carbonaceous material can be used to make activated carbon and several methods are available to activate or make internal pores accessible for adsorption. The starting material is first charred in the absence of oxygen to drive off volatiles and to end with a high carbon content material. Subsequent treatment consists of activation, generally with steam to open internal pores to the exterior of carbon particles. Sometimes chemicals are used to remove residual materials from the carbon. Once available, activated carbon can be powdered, agglomerated, extruded or otherwise processed for specific applications. Even though laboratory adsorption feasibility studies can be run to predict performance under conditions of use, actual use is often required to determine the efficacy of a specific carbon.

Fly ash derived carbon was evaluated for two potential activated carbon uses under the current project. The first was as a traditional activated carbon based on related work performed

for the Michigan Department of Environmental Quality. The second was based on previously observed mercury vapor adsorption on fly ash carbon by the investigating team. A Ph.D. dissertation "Control of Mercury Emissions using Unburned Carbon from Fly Ash: Adsorption Mechanisms and Control System Development" resulted from this project.

Activated Carbon

An exploratory test was conducted in the laboratory to evaluate the equipment and procedures required to activate a carbon sample obtained from the fly ash beneficiation discussed earlier. Eighteen grams of carbon were loaded into an oven where it was heated under a nitrogen atmosphere from 25°C to 900°C at a heating rate of 5°C per minute. Activation was completed by steaming the carbon at 900°C for three hours using a flow rate of approximately 1 ml of water per minute. Finally, the oven was cooled to room temperature and the activated carbon sample was left in the oven under nitrogen overnight. A plan was then developed for evaluating the activated carbon.

The evaluation consisted of two tests, each conducted on two fly ash carbon samples recovered from Consumers Power Company ash. Carbon A was from a beneficiation trial that recovered 65% of the carbon and Carbon B was the result of a 75% recovery run. Activation studies were conducted in the same micro-computer controlled furnace under nitrogen. The steam flow rate was 0.96 ml per minute. Samples of the carbons were heated to 900°C at a rate of 10°C per minute and held at temperature for 60, 120 and 300 minutes. to determine the optimum carbon to steam (C/S) ratio. The activated carbons thus produced were evaluated by using ASTM procedures to determine the density, surface area, absorptivity (iodine number), pore size distribution, heavy element content, water solubles and ash content. Methylene blue tests, another way to measure carbon activation, using an ultraviolet visible analytical unit were conducted and compared to iodine numbers¹. Once the optimum C/S ratio was determined, the effect of temperature upon activation was evaluated by processing the samples for two hours at 300°C, 600°C, 800°C, and 900°C.

Activation Time Effects

Fly ash carbon samples A and B were activated with steam for various times. The results are summarized in Exhibit 50 and results indicate that the activated carbon yield decreases as the activation time increases for both carbon samples. For Carbon A, the Iodine number increases as the activation time increases (Exhibit 51), possibly due to increased pore volume caused by the opening of pores during steaming. It appears that an activation of 3 hours or more at these conditions is needed for Carbon A. to obtain the maximum Iodine number. The iodine number for Carbon B started to level off at 88.3% yield (Exhibit 52). This indicates that activated carbon

¹The iodine number is defined as the amount of iodine (mg) adsorbed by 1.0 g of carbon at a residual concentration of 0.02 N. The result is a good indication of the micro porosity and is often correlated to BET surface area values.

made from Carbon B reached its maximum iodine number after 2 hours of activation with steam at 900°C.

Exhibit 50 Activation Time Effects on Properties of Fly Ash Activated Carbon					
Sample	Activation Time (Min.)	Yield (%)	Ash Content (%)	Iodine Number (mg/g AC)	Apparent Density (g/ml)
Carbon A			37.19		
No. 1	60	96.02	38.49	55.71	0.462
No. 2	120	95.03	38.70	54.54	0.464
No. 3	300	89.25	40.78	195.43	0.426
Carbon B			29.49		
No. 1	60	94.46	30.96	62.75	0.424
No. 2	120	88.28	34.73	210.85	0.402
No. 3	300	83.88	35.09	211.47	0.375
Commercial					
WPH: (Calgon)				664.38	

Note: Carbon was activated at 900°C for the times given in the table at a heating rate of 10 °C/min. The steam flow rate was 0.96 mL H₂O/min.

Exhibit 51 Effect of Activation Time on Yield and Iodine Number for Carbon A

Exhibit 52 Effect of Activation Time on Yield and Iodine Number for Carbon B

Exhibits 53 and 54 indicate Carbon B has a somewhat lower yield and a higher iodine number than Carbon A at shorter activation times. In other words, Carbon B appears to be a better raw material than Carbon A from which to make activated carbon under the same conditions. The iodine number achieved in either case however was only about one-third that of commercial products such as obtained from the Calgon Company.

Exhibit 53 Yield of Carbon A and Carbon B

Exhibit 54 Iodine Numbers of Carbon A and Carbon B

Activation Temperature Effects

Fly ash carbon was activated at temperatures of 300°C, 600°C, 800°C, and 900°C. The results are shown in Exhibits 55 and 56. No activation of either carbon occurred at temperatures below 600°C. Higher temperatures of activation resulted in higher degrees of activation as measured by iodine number.

Exhibit 55 Temperature Effect on Yield and Iodine Number - Carbon A

Exhibit 56 Temperature Effect on Yield and Iodine Number - Carbon B

Iodine numbers for both carbon samples were about the same, except at the 900°C activation temperature where Carbon B activity was noticeably higher than that of Carbon A, as shown in Exhibit 57. However, under the same activation conditions the activated carbon yield was higher for Carbon A (Exhibit 58) because of its higher ash content.

Methylene blue testing correlated closely to the iodine number results and verified that the activated carbon obtained from fly ash is a low grade material. Exhibit 59 shows the correlation between iodine number and methylene blue for a range of different activated carbon products.

The yield of the activated carbon in the preliminary test was 83.3% and the absorptivity of methylene blue was 60 grams per gram of activated carbon. The data, reported above, even though preliminary, imply that activated carbon could be made from fly ash derived carbon.

Exhibit 57 Temperature Effect on Iodine Number

Exhibit 58 Temperature Effect on Yield

Exhibit 59 Correlation Between Iodine Number and Methylene Blue

Fly Ash derived carbon as a mercury adsorption media

This section summarizes the results of the Ph.D. dissertation “Control of Mercury Emissions Using Unburned Carbon from Fly Ash: Adsorption Mechanisms and Control System Development.” [13]

The total worldwide mercury discharge to the atmosphere has been estimated to be 6,100 metric tons per year of which 2,500 metric tons originate from natural sources. Anthropogenic activities contribute the remaining 3,600 metric tons. [14]

The major human sources of atmospheric mercury include the combustion of fossil fuels such as coal and natural gas, waste sludge incineration, cement manufacturing, chlor-alkali cells for producing caustic soda and chlorine from brine, and metal extractions. Approximately 85% of the emissions are from fossil fuel combustion facilities and municipal solid waste incinerators. [15] After being released from a source, mercury and its compounds will undergo transportation and transformation in the environment, creating a potential threat to human health and the ecosystem. Mercury can enter the environment by simple transport as metallic mercury vapors, as transformed volatile organic compounds, chemical transformation into more soluble salts or other compounds, or as a combination of these processes. The steady evaporation of mercury into the atmosphere at mild temperatures stems from its high volatility.

In combustion processes, such as electric utility boilers and waste combustors, the majority of the mercury, along with other trace elements, is released in gas form from the parent fuels at high temperatures, about 1100°C. As the combustion gas cools, a fraction of the mercury vapor may condense on ash particles, while the remainder may remain in the vapor form.

Depending on the fuel type, combustion condition, and the cooling environment, the partitioning of mercury species may vary. The chlorine content of the fuel and the oxygen content of the flue gas, for example, has been found to influence mercury speciation. In general, most mercury in municipal waste combustion flue gas is present as mercuric chloride because the waste contains sufficient chlorine to oxidize mercury to a mercuric form. [16] In contrast coal contains much less chlorine, thus most mercury in the electric utility flue gas is elemental. Any nitrous

oxide present may oxidize the mercury to nitrate while sulfur dioxide reduces it back to elemental mercury.

Mercury in electric utility flue gas is reported to be predominantly in the vapor phase, with only about 5-15% associated with the fly ash particles. [17,18] The air pollution control devices used to control stack emissions have been found to affect mercury emissions into the atmosphere. Three different types of air pollution control devices are currently being utilized in the utility industry and waste combustion systems. These devices are particulate collection units, flue gas desulfurizing systems and NO_x control systems.

Different devices employ different mercury removal mechanisms. In a particulate collection device mercury is removed along with fly ash particles on which mercury had been adsorbed or condensed. Thus, the more effective a device in removing particles, especially fine particles, the higher the mercury removal efficiency. With wet scrubbing, mercury is removed by dissolution in the scrubbing liquid. The removal efficiency is dependent upon the solubility of the mercury species and the properties of the liquid. Not enough data is available to evaluate the impact of NO_x control systems on mercury removal.

One method for controlling mercury emissions from fossil fuel combustion is by use of carbon injection into the combustion flue gas to adsorb mercury upstream of particulate collection devices. The mercury loaded carbon is then collected by the particulate device along with the fly ash. It has been reported that over 90% reduction in mercury concentrations is achievable by applying this technology. Also from the literature, it appears that unburned carbon in fly ash can be successfully used in the injection control process. [19]

Cost evaluations by EPA indicate that the cost of removing one pound of mercury from utility flue gas is \$131,000 to \$299,000 for activated carbon filter beds and \$5,240 to \$28,000 for activated carbon injection. [20] These rates make activated carbon the major cost component of these systems, thus a search for a source of low cost carbon is of paramount importance. In the adsorption process, the carbon-mercury contact time is very short and adsorption equilibrium may be difficult to reach. Thus, carbon injection rates of 1,000 to 10,000 times the mercury emission rate are necessary at the flow rates and dilution factors involved. The micro-pores in activated carbon have less of a chance to adsorb mercury because of diffusion limitations. As a result, the potential adsorption capacity of the activated carbon will not be effectively utilized. The adsorption kinetics may be faster in the case of the unburned carbon from fly ash because it is predominated by macro pores.

Studies conducted by several researchers indicate that using unburned carbon from combustion processes can be an alternative to commercial activated carbon to capture mercury from combustion flue gas. Some of the work investigated the injection of fly ash into flue streams. This practice relies on the presence of minority amounts of unburned carbon in ash and the ultimate disposal of huge quantities of mercury contaminated inert material in which the carbon and adsorbed mercury is contained. Other work was based on the collection of combustion soot and its introduction into mercury contaminated flue streams. The works

described in the literature are mainly theoretical without discussion of commercial factors such as disposal or post treatment of mercury contaminated carbon, material availability or cost.

Many types of carbon, such as activated carbon and other types of chars and carbon black form a group of carbonaceous materials of which the structure, and the properties depending on it, are more or less similar to the structure of graphite. The unburned carbon in fly ash is evolved from coal and has undergone a heating process similar to that required to produce activated carbon or carbon black. The morphology of fly ash derived carbon is seen in Exhibit 60 to have a porous structure and irregular shape. It is predominated by macro pores, with the opening size ranging from 1 μ m to 10 μ m. Each of the carbons investigated in the present project exhibited similar characteristics.

Exhibit 60 Morphology of Fly Ash Derived Carbon

The porous structure and accompanying high surface area indicate the carbon is, potentially a low cost adsorbent or precursor to activated carbon. From the photomicrograph it can also be observed that the carbon is contaminated by glass spheres. These may have been entrained in the carbon during separation or, most likely, have been fused with the carbon particles during combustion. The spheres are thought to possibly catalyze mercury adsorption on the carbon. On the other hand, if the spheres hinder adsorption, the carbon could be ground and scrubbed to liberate them for separation. Additional carbon properties related to adsorption activity are presented in Exhibit 61.

Compared to activated carbon, the unburned carbon from fly ash has a limited pore volume and low volume ratio of micro pores to macro pores. The unburned carbon used in this project had a specific surface area approximately one three hundredth of activated carbon and a third as much total pore volume. It can be concluded that unburned carbon has a limited surface area and is characterized by macro sized pores. Since surface area is related to adsorption capacity and macro pores are important for the passage of adsorbates, these carbons are expected to have fast overall adsorption kinetics with a reasonable adsorptive capacity. Also, larger pores

allow ease of regeneration. Thus, fly ash derived carbon may be more suitable for adsorption of medium and large molecules such as mercury.

Exhibit 61 Surface Area and Pore Size of Activated Carbons (nitrogen adsorption method)			
Characteristics	Carbon		
	AEP	DE	NPC
BET surface, m ² /g	25.60	18.71	58.33
Pore surface area 17-3000 , m ² /g	20.26	12.83	38.43
Micropore area, m ² /g	3.87	4.78	16.94
Pore volume (17-3000), ml/g	0.0325	0.0227	0.0586
Micropore volume, ml/g	0.0015	0.0021	0.0074
Average pore diameter (by BET),	49.97	48.87	43.74
Average pore diameter (by sorption),	64.23	71.15	61.01

Experimental Work Summary

The six different sources of carbon were examined and presented with physical properties as reported in Exhibit 62 were determined. AEP-F-L and AEP-F-H are minus 100 mesh carbon samples obtained by processing AEP ash with froth flotation. AEP-F-L was dried in air at 104°C whereas AEP-F-H was heated at 400°C for 4 hours. For comparison, two commercial activated carbon samples, BPL and F400 from Calgon Carbon Corp. were also tested. Under controlled conditions with nitrogen as a carrier gas and mercury concentration of about 0.45 mg/m³, carbon derived from the AEP and DE ashes had higher adsorption capacity for mercury than either of the commercial carbons.

Exhibit 62 Properties of Activated Carbon							
Carbon Samples	Avg. Size m	Density g/cm²	Surface area m²/g	Hg ppb	LOI %	S %	Remarks
AEP	187	1.98	25.60	645	80.9	0.81	+100 mesh
DE	270	2.01	18.71	924	73.4	0.59	+100 mesh
NPC	312	2.01	58.33	388	70.1	0.48	+100 mesh
AEP-F-L	62	1.98	22.66	620	67.7	0.69	-100 mesh
AEP-F-H	62	1.98	87.84	620	67.7	0.69	-100 mesh
BPL	4x10 mesh			≤5			Calgon
F400			946.66				Calgon

Characterization of the various carbons shows that NPC carbon had the largest surface area and more pores than the more effective carbons. The commercial carbons had the largest such characteristics. These data imply that something other than surface area and pore volume is controlling the adsorption of mercury on the carbons.

The use of fly ash carbon to capture mercury from coal combustion flue effluent was not designed to be part of the coal combustion by-product utilization project. Nevertheless, the work reported here was undertaken because of the importance of controlling mercury in the environment and its relationship to fly ash and the electric utility industry. Additional work needs to be undertaken to more fully understand the adsorption mechanisms of mercury on carbon and to determine how carbons from coal combustion can be treated for uniform and consistent performance.

Conclusion

In conclusion it can be said that:

1. Activated carbon can be produced from the fly ash separation carbon product.
2. The highest yield obtained was 83.3% and was for a carbon concentrate very high in ash. The absorptivity of methylene blue by this activated carbon was 60 grams per gram of activated carbon.
3. Increased activation times increased the Iodine Numbers of carbon products but the increases were accompanied by decreases in carbon yield.
4. The highest Iodine Numbers were achieved when activation was carried out at 900°C.
5. None of the fly ash recovered carbons produced Iodine Numbers as high as commercial products. This may be attributed to the high ash content (over 30%) of fly ash activated carbon, suggesting that further cleaning of the carbon concentrate may improve its quality.

Metal Matrix Composites

Introduction

Aluminum metal matrix composites represent an attractive, high-value-added, future market for processed fly ash. Over the last decade, discontinuously reinforced aluminum metal matrix composites have emerged as potential engineering materials for applications in a number of markets, including automotive, aerospace, electronic packaging and recreational products. These composites consist of a metallic aluminum matrix reinforced with blended-in hard ceramic particles. These ceramic particles typically increase both the strength and modulus of the aluminum alloy, as well as lower its coefficient of thermal expansion. They also produce a substantial increase in the wear resistance of the alloy.

Examples of current discontinuously reinforced aluminum composites include Chevrolet Corvette and GM S/T pick-up truck drive shafts, Plymouth Prowler brake rotors and GM EV-1 brake drums, Toyota diesel engine pistons, guide vanes in Pratt & Whitney 4000 series jet engines, electronic packaging applications in both Motorola Iridium satellites and GM EV-1 vehicles, as well as bicycle components and golf clubs from several producers. [21]

Aluminum composites exhibit very attractive engineering properties, but they currently cost substantially more than alternative engineering materials. Accordingly, there is a well-recognized need to reduce the cost of aluminum composite materials. Many of the current composites are produced using relatively expensive alumina or silicon carbide reinforcements. Therefore, work was undertaken to assess the potential for using cleaned, sized fly ash as a low-cost alternative for these higher-cost ceramic additives. As-received ash, with its high residual carbon content and wide particle size distribution, is not well-suited for most composite applications. The residual carbon, due to its porous morphology, is likely to degrade material properties significantly and the wide particle size distribution promotes inhomogeneous mixing of the metallic and ash phases. Ash beneficiation, however, can overcome these limitations.

Preliminary Investigations

Aluminum-fly ash components can be produced using several different fabrication routes. Powder-based approaches are attractive because they can be used to produce composites with a wide range of fly ash contents and are particularly suitable for producing large quantities of small components such as one might use as wear-resistant inserts in aluminum castings. In addition, powder-based composite processing involves only limited contact between fly ash and molten aluminum, minimizing the potential for detrimental interfacial reactions between the ash and the matrix alloy.

Accordingly, this study focused on assessing the potential for using powder processing to produce aluminum—fly ash composites. Initial exploratory studies were performed using two different aluminum alloy compositions as matrix alloys. These two compositions are shown in Exhibit 63. Both were produced using a blended elemental approach, i.e. by mixing together fine, elemental powders of each alloy constituent to produce a homogeneous powder blend. These

blended elemental matrix alloys were then combined with 10 vol% beneficiated, -635 mesh (-20 micron) fly ash to produce composite powder mixtures.

Exhibit 63 Nominal Composition of Aluminum Composite Matrix Alloys					
Alloy	Al wt%	Cu wt%	Mg wt%	Si wt%	Mn wt%
6092	97.60	0.80	1.00	0.60	0.00
2124	93.50	4.40	1.50	0.00	0.60

The beneficiated ash was found to exhibit good flowability and to mix well with the matrix powders, presumably due to its nearly spherical shape. Die compaction, sintering and heat treatment studies were then carried out to develop appropriate shapemaking protocols for these composite powder mixtures. Net-shape pressed-and-sintered tensile bars were produced from the aluminum-10 vol% ash composite blends using these protocols. These bars were tested in accordance with ASTM standard E-8. In addition, a small, net-shape statuette was produced by cold isostatically pressing the composite blend into a shaped preform and then vacuum sintering this preform under the same conditions as those used for the tensile samples. This statuette, as well as other items produced by machining shapes from consolidated aluminum-fly ash powder billets, are shown in Exhibit 64.

Exhibit 64 Aluminum Fly Ash Composite Shapes Produced at the IMP

A representative fly ash/aluminum metal matrix composite microstructure is shown in Exhibit 65.

Exhibit 65 Powder-based 2124/fly Ash/10p Al MMC Microstructure

Heat treatment studies showed a clear difference in behavior between the materials containing the 6092- and 2124-matrix alloys. Exhibit 66 shows the Rockwell E hardness of sintered, solution-treated test coupons aged at 170°C for times ranging from 2 to 16 hrs. Each point represents the average of hardness values obtained on duplicate test samples. Note that both the unreinforced 6092 matrix alloy and the 2124/Fly Ash/10p composite exhibited hardness values greater than 80 R_E after aging times of at least 8 hours. In contrast, the 6092/Fly Ash/10p material showed essentially no increase in hardness during artificial aging.

Exhibit 66 Aging Characteristics of Al-Fly Ash Composites

Scanning electron microscopy of the fractured tensile samples showed silicon-rich areas surrounding fly ash particles, with little or no silicon present in the surrounding matrix. In addition, possible diffusion of magnesium and copper into the fly ash particles was observed. Both observations suggest possible reactivity between the 6092 matrix and the fly ash.

reinforcement. In contrast, the 2124-matrix composites showed no evidence of extensive reaction between the matrix and the ash.

The tensile properties observed on these initial 6092- and 2124-based composites are shown in Exhibit 67. Both the low tensile strengths and wide range in elongations observed in these materials suggest inconsistent heat treatment response and/or other processing irregularities. Accordingly, wear testing of these materials was not carried out. Rather, efforts were re-directed toward developing improved processing protocols for the composites.

Exhibit 67 Tensile Properties of Pressed and Sintered Aluminum Matrix Composites				
Tensile Bar Set #	Composition	Sinter Density (% theoretical)	Ultimate Strength (psi)	Elongation (%)
1	6092 10 v/o Fly Ash	87.7	12,393	7.40
2	6092 10 v/o Fly Ash	87.7	17,867	5.54
3	2124 10 v/o Fly Ash	91.4	18,385	2.41
4	2124 10 v/o Fly Ash	90.7	14,067	15.0
5	2124 10 v/o Fly Ash	89.9	23,663	2.48

Microstructure examinations of both the 6092- and 2124-based composite tensile samples showed them to contain evidence of excessive outgassing during the latter stages of sintering. It is well-recognized within the powder metallurgy community that metallic aluminum powders will evolve moisture, hydrogen and other volatile species during consolidation processing. In conventional powder metallurgy processing, this outgassing is not particularly troublesome since the compacts exhibit enough residual, interconnected porosity to allow these gases to escape with little difficulty. Powder-metallurgy-based aluminum composites, however, show little densification during conventional sintering operations due to the restraining effect of the ceramic reinforcement. Accordingly, it is advantageous to cold-press these materials to higher green densities before sintering. In addition, the ceramic reinforcement may outgas more than a corresponding amount of aluminum. Both factors increase the likelihood that gas evolution from the powder blend may damage the compact during sintering.

Second-Generation Processing

Based on these heat treatment, mechanical testing and metallographic results, it was decided to focus subsequent development efforts on the 2124-based matrix alloy and to adopt a new composite processing protocol to minimize detrimental outgassing effects. This new processing route is shown in Exhibit 68. The elemental matrix powders were first blended with beneficiated, sized fly ash. This composite powder blend was then vacuum outgassed at elevated temperature to remove residual volatiles prior to cold compaction. Next, the material was cold

isostatically pressed into 58 in. (16mm) dia. cylindrical preforms. These preforms were canned in evacuated copper cans. Graphite foil was used as a diffusion barrier between the aluminum and the copper can. The canned samples were then hot isostatically pressed (HIP'ped) at 60,000 psi (414 MPa).

Exhibit 68 Second Generation Al-Fly Ash Composite Processing

Initial samples were HIP'ped at 500°C. Metallographic evaluation of these materials, however, showed large residual copper particles approximately 30 to 60 μ in size, indicating insufficient liquid phase formation at this temperature. Accordingly, subsequent samples were HIP'ped at 560°C, slightly above the temperature of the binary aluminum-copper eutectic. These materials showed clear evidence of significant liquid formation and a much more uniform distribution of copper. After hot isostatic pressing, each material was mechanically decanned and machined into standard cylindrical test coupons. These coupons were heat treated to a T-6 (peak

strength) condition by solution treated at 513°C for 1 hour, cold water quenching, and aging at 170°C for 18 hours. The heat treated coupons were then tested in accordance with ASTM standard E8.

Composite test pieces were fabricated containing 0%, 10 vol% and 20 vol% fly ash. After HIP consolidation, the unreinforced 2124 powder and the 2124/Fly Ash/10p composite exhibited densities of 88.2% and 94.5% theoretical, respectively, indicating that these materials did not densify effectively during processing, perhaps due to leakage of the HIP can. The 20 vol% material exhibited a density of 97.3% theoretical. For comparison, similar 2124/Fly Ash/20p composites which were cold isostatically pressed and then sintered rather than HIP'ped exhibited a density of 88.0% theoretical. This 2124/Fly Ash/20p—T-6 composite exhibited a tensile strength of 46,500 psi (321 MPa) with 0.7% elongation. These properties are comparable to standard commercial pressed and sintered aluminum materials. Alloy 201AB-T6² (the composition of this alloy is nominally 4.4Cu-0.8Si-0.5Mg-Bal Al) with 1.5% admixed pressing lubricant, for example, has a tensile strength of 48,100 psi (330 MPa) and an elongation of 2.0% when processed to 97% theoretical density. (Metals Handbook, Ninth Edition—Vol. 7 Powder Metallurgy, ASM, Metals Park, OH, 1984. p. 742.) The somewhat lower elongation of the fly ash composite is characteristic of reinforced metal matrix composites. It was not possible to perform wear testing on this second-generation 2124/Fly Ash/20p—T-6 composite under the program. The presence of the hard, spherical fly ash reinforcement, however, is expected to provide this composite with substantially greater wear resistance than traditional unreinforced aluminum materials such as 201AB-T6.

Conclusions

These results demonstrate that fly ash can be used effectively as a reinforcing phase in powder-metallurgy-based aluminum composites. With appropriate processing, the materials possess tensile properties competitive with traditional aluminum powder metallurgy materials while exhibiting excellent potential for substantially-improved wear performance. In order to fully exploit the cost-savings potential of these composites in applications such as wear inserts for automotive aluminum castings, however, there is a need to further develop low-cost processing protocols for the material.

Alternate high-silicon matrix compositions and high-temperature sintering practices need to be explored in order to minimize the need for hot isostatic pressing of high-volume production components. In addition, the wear behavior and machinability of these composites needs to be more fully characterized. Effects of variations in fly ash size, size distribution and cleanliness on engineering performance of the materials also need to be more fully explored.

²The composition of this alloy is nominally 4.4Cu-0.8Si-0.5Mg-Bal Al with 1.5% admixed pressing lubricant.

Market and Economic Analysis

Introduction

Beneficiation of fly ash produces two groups of commercial materials, clean ash and recovered components of the clean ash. The largest volume use for clean ash is as a partial replacement for cement in concrete mixtures. Since the 1930's the siliceous characteristics of fly ash from coal combustion have been recognized as useful in concrete. Fly ash concrete was originally used in massive structures such as dams. Eventually its structural properties were better understood and it found its way into large buildings and other structural concrete applications. The use of fly ash received additional emphasis since the late 1970's with enactment of the Resource Conservation and Recovery Act and increased emphasis on the recovery and reuse of waste materials in general.

Fly ash is used with cement in three basic ways: as a raw material in the production of cement clinker, interground with clinker, or blended with cement. When used in the manufacture of clinker, fly ash provides silica and alumina materials for the cement proper. The interground and blending uses are physical processes while the pozzolanic properties of the ash are exploited to reduce costs and improve cement performance.

Fly ash may also be used directly as an aggregate in concrete, primarily concrete block manufacture. Ash can be sintered into a lightweight coarse aggregate for use in concrete and brick manufacture. Quality control during cement production and concrete preparation, and consistency of materials have long been recognized as important to predicting the final performance of fly ash cement and concrete products. Air classification has long been used to separate fly ash by particle size. However, this process does not effectively separate fly ash into its components because of insufficient density differences and because of the manner in which the components are combined.

From the perspective of the cement industry, carbon is the most deleterious component of fly ash because it interferes with the chemical agents added to improve the freeze thaw characteristic of concrete. The most effective means of removing carbon from fly ash is through the use of flotation. Flotation produces streams of clean ash and carbon. The fly ash constituents must be separately marketed to make flotation financially attractive. For evaluation purposes the revenue stream of a fly ash beneficiation plant needs to also recognize the savings of forgone landfill disposal costs. Two major markets, industrial fillers and carbon, were the focus of the market phase of the current project.

Industrial Fillers

Overview

There are two general classes of fillers, functional and non-functional, depending upon the role of the filler in the final product. Non-functional fillers are used as bulking agents, extenders and cost reducing agents. Functional fillers serve some purpose based on the physical or chemical characteristics of the filler material. Functional fillers are added to materials for specific purposes, and, as expected, command higher prices than bulking agents.

Approximately 5 million tons of ground calcium carbonate are produced each year as filler in North America. This amount is consumed by a number of industries, each with a preferred size range as indicated in Exhibit 69. Ground calcium carbonate prices range from \$20 per ton for coarse material to over \$300 per ton for ultra fine specialty coated material. The present project was concerned with the technical evaluation of fly ash as a mineral filler for the plastics industry because of the functional characteristics of the ash. Commercial aspects of this application and market attributes of other related applications are presented below.

Exhibit 69 Calcium Carbonate Filler Size Range Preferences by Industry			
Sector	Preferred Micron Size	Million Tons per Year	Value (\$000,000)
Plastic	0.5-1	0.9	110
Paper	0.5-1	1.0 +	
Paint	0.5-1	1.0	230
Sealants	12-22	0.9	80
Carpet Backing	22-40	0.7	20

Filler Preparation

The most important attribute of calcium carbonate as a filler is its mean particle size. Other important attributes include brightness, oil adsorption and crystal shape. In plastics, particle size plays an important role in the strength and rheology of the material. In paper applications particle size affects fiber strength, and in turn the loading rate. In paint, particle size affects brilliance and final gloss.

Ground calcium carbonate is classified into several main grades.

1. By-product fines from aggregate production,
2. By-product from aggregate but with an emphasis on filler sized material,
3. Specifically produced 2-3 micron material from ball and pebble mills,
4. Wet ground and cycloned to produce less than 2 micron material,
5. Wet ground material less than 0.5 micron.

Additional grades of material are commonly made by using flotation to improve brightness and coating processes to increase dispersion of the fine particles or to impart special features such as light reflectance or to affect surface energy and the adherence of finishes such as paint.

Production and Marketing Issues

The ten largest calcium carbonate producers account for approximately two thirds of North American production, an additional fourteen companies account for the remaining one third. During the early 1990's the calcium carbonate industry experienced a recession that saw consumption and prices drop by 15% from year before highs. The lower prices apparently spurred consumption, since by 1994 supplies of calcium carbonate were short and the industry increased production capacity by 50%. The expansions increased competition within the industry and several producers have shifted production to finer grades where the competition is not as fierce. These market shifts have tended to reduce the number of producers in the industry. Smaller suppliers tend to focus on specialty regional or local markets where their higher unit costs are less of a concern than when competing head-on with national producers of more generic or commodity mineral grades. The large companies have succeeded by being able to offer customers a range of filler grades and types of mineral fillers.

Fly ash fillers are solid or hollow spheres and are most likely to be used in markets where spherical particles are used commercially, thus mineral fillers are not widely used in rubber because their shape is not conducive to adding reinforcement. Some improvement is realized however, if the filler is treated with coupling agents such as silane. In general however, carbon is the preferred rubber filler especially with tires, where mineral filled rubber has been shown to exhibit reduced wear resistance and lower strength. Exhibit 70 presents a summary of the principal industries that use mineral fillers and some information about their requirements.

Exhibit 70 Principal Mineral Filler Consuming Industries			
Industry	Desired Filler Characteristics	Annual Use (metric t/y)	Currently use
Paper	very fine, brightness	3.6 million	kaolin, CaCO_3
Paint and Coatings	stringent quality, high bulk, low oil absorption, high brightness, 45	0.6 million	CaCO_3 , kaolin, talc
Rubber	reinforcing, fly ash carbon may be useful but much work need to be done		CaCO_3 , kaolin, carbon black
Plastics		1 million (0.5 is CaCO_3)	CaCO_3 , kaolin, talc, some fly ash
Putty, Caulks, Sealants			CaCO_3
Dry Wall Compounds			CaCO_3
Adhesives			low value CaCO_3
Carpet Backing			
Floor Tile	granular, coarse, good color, controlled particle size		

Plastics Industry

Approximately 5 billion pounds of calcium carbonate is used by the plastics industry each year. This is the most commonly used filler and its characteristics appear to be suited to substitution by quality controlled clean ash. Elongated or fibrous fillers are used to create reinforced composites with superior physical properties. More spherical fillers such as calcium carbonate are used primarily as extenders of four primary resins, polypropylene, polyvinyl chloride, polyamide and thermoplastic polyester. PVC is the largest resin user of fillers and it used to make items such as flexible wire coverings, plastic pipe, and floor tile among other items. Loading rates may range from as low as 1 to 5% for rigid items up to 80% in flexible products.

Calcium carbonate is widely used in resins because of its effect on product flexure, surface finish and viscosity during product molding or formation. The resin industry has identified several main filler attributes that affect final product quality. Among them are particle size distribution, dispersibility, equipment abrasion, compound properties, and cost. If the fillers are used as structural materials, additional properties such as compatibility with surface coupling agents and linkage between resin and filler also become important. These are of secondary importance to calcium carbonate since its shape limits its use to an extender type filler rather than as a structural filler.

Plastics Product Manufacture

The structure of an industry affects the strategy for introducing a new or replacement material. For example, plastic product manufacturing involves three primary players, polymer manufacturers, compounding companies, and end product manufacturers. Polymers are manufactured primarily by several large corporations such as DOW, GE and DuPont. These companies produce resins in pelletized, granulated or liquid form that compounders blend with a host of other materials such as fillers, colorants, stabilizers and fire retardants to meet end product performance demands. These compounds may be the resin producers themselves or any number of specialty companies that rely on their knowledge of end product producer needs to blend compounds that meet specific production requirements. Frequently the end product of compounding is a highly concentrated filled material that is blended with additional resin at the molding machine.

End products are produced by a myriad of injection molders, many of which have little technical knowledge of the compounds they are using. They rely on compounders or their own customers to specify the proper compound for them to use for specific products. Thus, compounders and end product customers are the important decision makers within the plastics industry of concern to filler manufacturers.

Compounding has become an increasingly important factor in plastics manufacturing. This is the result of rising resin prices, the need to add additional agents to control the behavior of

resins during molding, a general move to the production of engineered plastics products, and a general increase in the understanding of the technical factors of resins, compounding and molding.

Calcium carbonate is particularly attractive to the plastics industry because of its relatively low cost, low absorption of resin, dispersibility, relative high brightness, softness and low abrasiveness. Typical loadings range from 20 to 200 parts per 100 parts of resin (phr) in thermoset plastics and from 10 to 50 phr in molding plastics. Its low cost, and low absorbency also make calcium carbonate attractive to the sealant industry.

The requirements of fillers are less stringent for the sealant and carpet industries than for use by the plastics industry. This is reflected in the price. The whitest grades are used by the paper industry where it commands superior prices. Calcium carbonate is used by the paint industry as an extender of TiO_2 , the standard white pigment. The refractive index for such use is substantially below 1.75.

Additional factors effecting the marketability of a filler includes the fact filler users have become more technically advanced in recent years and place increased demands upon suppliers to provide more technical assistance. As a result, suppliers have increased their R&D efforts and technical support. Also as the relationship between filler use and final product characteristics are better understood, customers are demanding more consistent quality from suppliers. In addition, the focus on recycling has placed new constraints on the use of fillers.

Lower Value Applications

The asphalt roofing market consumes the single largest amount of calcium carbonate fillers. Approximately 65% of the 7.5 million ton North American filler market is represented by the roofing industry. Mineral fillers are used primarily to lower the cost of the final product, and to add weight and bulk to the final product. Fillers lower the viscosity of the asphaltic material during roofing production. This makes the product easier to form during production and increases wear resistance of the final product.

Neither fly ash color or brightness are critical for this application. The majority of US asphalt roofing production is in the South, thus minerals, including fly ash, from this part of the Country would most likely be used by the roofing industry. The low quality requirements for roofing fillers translates into market values of less than 1 to 2 cents per pound for this market.

Carpet backing is another example of a low value application for mineral fillers. Fly ash color would not be critical for this use. Particle size is the most critical specification. Particles should be less than 325 mesh. Loading rates of 4 to 5 part filler to 1 part resin are common. Anticipated prices would be in the range of 2 to 5 cents per pound.

Summary

One of the most important physical characteristics of fillers is size distribution of filler particles. In general, particle size and size distribution determine the application. Appearance factors such as brightness, oil absorption, wettability and mechanical property effects are influenced by particle size. The refractive index difference between filler and binder determines opacity and the degree of whiteness the filler imparts on the filled product. In applications where high volumes of fillers are used, variations in filler color and particle size can have a profound effect on filler acceptability by users.

Power plants are operated to achieve efficient generation of electric power within limits of air emission standards and other criteria. Thus, ash quality is at the mercy of plant operating conditions and is usually quite variable. The degree to which ash can be beneficiated to produce a stream of material consistent with market demands will control the ease by which the ash can be marketed. Ash that is of acceptable but of variable quality will always be viewed carefully by a marketplace that is becoming less tolerant of inconsistent quality.

Since fly ash is most likely to be a substitute for calcium carbonate rather than other filler materials, detailed information on its use for such purpose is presented in Exhibit 71 below.

Exhibit 71 Common Calcium Carbonate Attributes by Industrial Sector		
Sector	General Specifications	Price per ton
Paint	high brightness, medium size	\$250-270
Paper	high brightness, very fine	\$250-270
Rubber	white to off-color, medium to fine	\$100-125
Plastics	white, medium size	\$70-125
Putty, Caulking, Sealant	white	\$70-125
Vinyl Floor Tile	coarse to medium	\$30-60
Carpet Backing	white to gray, medium size	\$30-60
Roofing	off-color, medium size	\$20-50

Calcium carbonate used as mineral filler has no standard designation, however, the ASTM classification system for calcium carbonate pigments is a useful summary. The system is presented as Exhibit 72 as summarized by the Ontario Ministry of Natural Resources.

Approximately 50% of the calcium carbonate consumed by the plastics industry is used in vinyls. Floor tiles are one of the largest applications of this category. Requirements for this market include coarse ground light colored material of controlled particle size. This is a low value

application. Traditionally, polypropylene based plastics were talc filled. Now coated calcium carbonate is used at reduced cost and could be available to coated fly ash as well.

Exhibit 72 ASTM Pigment Grades of Calcium Carbonate				
	Grade I	Grade II	Grade III	Grade IV
Particle Size				
+325 mesh	0.005, 0.01	0.02	1.0	22
Particle Size (micron)	0.5-15.0 0.5-31	0.5-36.0 1.0-50.0	8.0	40.0
Mean Particles	3.0 - 6.5	7.0-12.5	13.0-17.5	36
Physical Properties				
Oil absorption	14.0-16.0 13.0-15.0	13.0-15.0 11.0-13.0		
Bulk Density	0.0443	0.0443	0.0443	0.0443
Specific Gravity	2.71	2.71	2.71	2.71
Refractive Index	1.59	1.59	1.59	1.59
Brightness (min)	96.0	94.0, 93.0, 93.0	85.0, 93.0	90.0

Other significant markets for calcium carbonate include putty, caulks and sealants. In these applications fillers extend the underlying resins and increase the flow of product during application. Color is not a major concern as long as it is reasonably light. Color is of less concern to the adhesive market since the final use of this product is generally out-of-view. These materials are approximately 50% calcium carbonate. Since color is not of major importance, and if particle size requirements can be met beneficiated fly ash may be particularly well suited to this application.

Carpet backing is the largest single user of calcium carbonate as a filler. Rather coarse off-color grades can be used at loadings of four parts filler to one part polymer. At the other end of the filler quality scale are glass and ceramic spheres. Even though these fillers are relatively expensive and the market for them is expected to grow, the volume pales when compared to the volume of fly ash. In addition, fly ash spheres are less uniform in size and shape than manufactured spheres.

The mineral filler market for which fly ash would most readily compete (calcium carbonate) is valued at about 4-5 cents per pound. The price has remained relatively stable for the past 15 years. In 1983 the general price range was \$60-100/ton. Today it is about \$70-115 for the most commonly used grades. Higher value niche markets exist, but they are relatively small and would be somewhat difficult to penetrate, given the probably strength of the relationship between

existing filler suppliers and their customers. In addition, the cost to perform special fly ash treatments necessary to meet high value market demands, such as fine grinding and classification may be difficult to recover.

Carbon

Introduction

Beneficiation of fly ash by flotation will result in a carbon product with an approximate carbon content of 80-85% as measured by LOI. Several potential uses exist for this material including as a high volume - low cost powdered activated carbon for odor control and mercury adsorption, as a rubber additive, and as a precursor to producing a reductant for metal refining. In contrast to the clean ash application discussed above, which are based on physical characteristics, the carbon uses depend upon chemical characteristics such as adsorption chemistry, reactivity to form high BTU fuel, or aspects of rubber chemistry.

The market potential of recovered fly ash carbon requires additional research before market potential can be adequately determined. Such research is critical because the use of the carbon may represent the operating market necessary to make fly ash beneficiation commercially viable. The present work investigated several potential uses for fly ash carbon that are worthy of further technical evaluation. They are discussed in the following paragraphs.

Activated Carbon

The current domestic market for activated carbon is approximately 250 million pounds annually. This total is approximately evenly split between powdered and granulated carbon. Even if fly ash carbon were to penetrate 10% of the existing powdered carbon market, it would require a small portion of the fly ash carbon potentially available. Existing activated carbon markets do not present a significant opportunity for carbon recovered from fly ash.

On average, pulverized activated carbon is a 50 cent per pound commodity with a range from 25 cents to \$2.20. The economics of fly ash beneficiation indicate the recovered carbon could sell for as little as \$0.08-0.10 cents per pound. This pricing range should greatly increase the market opportunities for activated carbon. However, the technical capability of the carbon must be more fully evaluated before the extent of the opportunity can be estimated.

It is known however, as a result of fundamental work performed in association with the current project, that fly ash carbon is more effective in adsorbing flue gas mercury than some commercial activated carbons. This application would be a tremendous business opportunity but, it is dependent upon the regulation of mercury emissions. Coal burning electric utilities have been identified as the largest remaining source of mercury emissions to the air. There may be a future role for fly ash derived carbon in the control of combustion based mercury emissions. Additional research in this area is required to determine the reasonableness of this application.

Odor Control

Opportunities of low cost ash carbon use also exist with odor control. Anecdotal evidence exists suggesting the benefits of low cost carbon control feedlot and other agricultural odors, and odors from municipal sewage and landfill operations. Meaningful estimates of the market opportunity associated with these applications is largely dependent upon the unknown efficacy of fly ash carbon to adsorb hydrocarbons.

The solid waste business is plagued by odors from several sources; disposal containers, transfer stations, standing trucks, landfill gas, reclamation and others. Citizens are often activists when it comes to odors as experienced by several communities. For example, Caroline County, Virginia, in 1996 was faced with a law suit seeking damages from noxious land fill odors and a Wisconsin company recently faced legal action from citizens of a small town who objected to odors from a fermenting process.

Typically odor control involves masking with a more pleasant odor, dispersion practices and expensive scrubbing systems. Malodorous gases from manure pits are a particular problem where animals are raised in confined space or in large numbers. Such farming practices are becoming more widely utilized because of the economies of scale involved. As a result, odors become particularly bothersome and the demand for corrective action is ever increasing.

The EPA has determined the composition of raw and digested sewage odors are associated with a limited range of organic compounds, acetic acid and hydrogen sulfide. Carbon adsorption has been proved effective in removing most of the offensive odors. It is not unreasonable to conclude fly ash carbon may also be effective in removing appreciable levels of sewage odors. No scientific evidence is known to exist on the effectiveness of fly ash carbon as a sewage odor control agent.

Metal Refining

Many primary metals are produced by reducing oxide ores or minerals to metallic form by chemical reactions involving carbon. The most common example of such practice is the use of coke by the iron and steel industry. Coke is a high carbon product of coal from which volatile materials have been removed by heating coal in the absence of air. Coke oven emissions are complex organic compounds, many of which are known carcinogens. After the volatiles are removed the carbon rich solid is quenched in water before being broken into sizes for commercial use. These operations result in wastewater and fugitive dusts that are environmental hazards. As a result US steel makers are seeking alternative technologies to traditional cokemaking as a way to avoid environmental problems and the need to rebuild ovens that are near or beyond their originally designed useful life.

Since 1980, domestic cokemaking has decreased from 46 million tons to 22 million tons in 1994. Faced with the prospect of spending hundreds of millions of dollars to rebuild aging coke

ovens to replace obsolete facilities, many steelmakers have abandoned cokemaking and now rely on outside suppliers. Today, only four North American steelmakers have excess coke production that is sold to others and only US Steel is selling large amounts of coke.

When fly ash is generated, power plant temperatures exceed those found in coking ovens, therefore, the residual carbon contains less volatiles and sulfur than coke. It is reasonable to expect the carbon can be used as a coke replacement without further processing except for some form of agglomeration to prevent it from “blowing up the stack” when added to metal refining operations. Potentially 3.5 million tons of coke could be produced from fly ash each year. This presents a value of \$180 to \$600 million dollars at current coke prices.

Coke produced from fly ash would also help reduce the increasing imports of metallurgical coke. The iron and steel industry are vital to the security of the nation. The supply of domestic coke would increase by 15% annually. These amount is approximately equivalent to the amount of coke sold by US Steel in 1994. Foundries and steel producers are concerned about future coke supplies and prices. The foundry industry has sponsored and has participated in cokemaking research conducted by Coal Technology Corporation and the DOE coal energy lab at the University of North Dakota. Earlier alternatives to conventual metallurgical coke include the FMC formcoke process and investigations of coke replacement by a number of fixed carbon sources. Carbon recovered from fly ash is free of volatiles, thus, coke made from this material would not emit carcinogenic emissions. Such is not the case when coke is made from coal.

Some companies have responded to coke shortages by increasing furnace efficiencies and by utilizing pulverized coal injection in the blast furnace to replace 25 to 40 percent of coke in the blast furnace. A major Midwestern iron foundry has adopted direct injection of carbon into cupolas as a standard procedure. In Germany, continuous injection has been under development for over two years as a disposal method for the flue dust and other foundry particulates.

The injection of fly ash derived carbon is a logical extension of the “alternative to coke” work in the iron and steel industries. In addition to being a promising market for fly ash carbon, these markets offer savings in BTU’s needed for iron production. Also, if cupola dust injection is coupled with carbon injection, productivity gains will be made because iron temperatures and melt rates will increase and carbon, iron, sand fines and zinc will be recycled.

Conclusions

Low NO_x combustion practices are critical for reducing NO_x emissions from power plants. These low NO_x combustion practices, however, generate high residual carbon contents in the fly ash produced. These high carbon contents threaten utilization of this combustion by-product.

This research has successfully developed a separation technology to render fly ash into useful, quality-controlled materials. This technology offers great flexibility and has been shown to be applicable to all of the fly ashes tested (more than 10).

The separated materials can be utilized in traditional fly ash applications, such as cement and concrete, as well as in nontraditional applications such as plastic fillers, metal matrix composites, refractories, and carbon adsorbents. Technologies to use beneficiated fly ash in these applications are being successfully developed.

In the future, we will continue to refine these separation and utilization technologies to expand the utilization of fly ash. The disposal of more than 31 million tons of fly ash per year is an important environmental issue. With continued development, it will be possible to increase economical, energy and environmental benefits by re-directing more this fly ash into useful materials.

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UTILIZATION OF LOW NO_x COAL COMBUSTION BY-PRODUCTS

Appendix to Final Project Report
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Appendix 1

Chemical Analysis by Size of As-received Ash Samples

As-Received Fly Ash Chemical Analysis by Size

D.C. Popko, 23 Apr 96

AEP As-Rec'd	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
Head	43.83	21.23	6.30	0.97	0.01	0.57	0.19	2.10	0.75	1.00	21.66
+100	24.01	12.55	3.96	0.32	0.03	0.16	0.17	1.13	0.18	0.49	56.99
+150	29.56	14.85	2.94	0.39	0.04	0.15	0.12	1.37	0.20	0.54	48.84
+200	32.83	16.75	3.06	0.48	0.03	0.13	0.09	1.62	0.31	0.58	43.11
+270	40.04	19.73	3.89	0.61	0.03	0.19	0.09	1.79	0.39	0.72	31.52
+325	38.56	20.01	3.79	0.62	0.03	0.19	0.05	1.81	0.51	0.77	32.66
+400	44.85	22.09	4.77	0.78	0.03	0.25	0.03	2.14	0.71	0.82	22.53
-400	49.18	26.41	6.89	0.93	0.04	0.35	0.00	2.50	0.95	1.08	10.68
BGE As-Rec'd	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
Head	55.08	28.51	3.63	0.80	0.04	0.00	0.25	2.07	0.99	1.40	6.22
+100	39.35	14.76	1.78	0.48	0.01	0.49	0.00	1.20	0.46	0.64	39.83
+150	49.74	22.83	2.28	0.73	0.01	0.93	0.03	1.86	0.61	0.93	19.06
+200	51.78	24.74	3.00	0.79	0.02	0.61	0.04	2.13	0.52		14.33
+270	53.45	26.96	2.74	0.85	0.01	0.65	0.04	2.28	0.60	1.18	10.23
+325	52.37	27.17	3.05	0.84	0.01	0.86	0.05	2.15	0.74	1.18	10.58
+400	53.68	28.14	3.73	0.95	0.02	0.83	0.03	2.10	1.33	1.44	6.76
-400	56.79	28.76	3.75	0.92	0.02	0.66	0.00	2.37	0.72	1.33	3.69
CPC As-Rec'd	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
Head	50.23	26.01	7.25	1.81	0.03	0.65	0.34	2.01	4.72	1.51	4.44
+65	45.35	23.59	4.55	0.84	0.03	0.50	0.16	1.39	1.64	1.07	19.09
+100	49.09	25.86	4.45	0.87	0.03	1.30	0.06	1.82	1.59	1.01	12.91
+150	52.30	25.31	6.22	0.93	0.06	1.06	0.08	1.81	1.72	1.10	8.42
+200	53.06	28.26	6.28	1.02	0.05	1.31	0.07	1.90	1.99	1.18	3.88
+270	54.46	27.04	7.14	1.11	0.04	1.39	0.10	1.82	2.45	1.24	2.20
+325	53.23	26.60	8.14	1.20	0.04	1.31	0.08	1.85	2.85	1.27	2.42
+400	52.85	25.94	8.08	1.25	0.04	1.22	0.07	1.83	3.07	1.25	3.40
-400	49.44	26.53	7.63	2.03	0.03	1.80	0.18	2.16	6.32	1.47	1.42
DE#2 As-Rec'd	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
Head	50.59	23.98	5.33	2.32	0.02	1.47	0.34	1.85	7.33	1.46	4.30
+65	22.30	11.38	3.78	0.63	0.05	1.91	0.15	0.54	2.16	0.56	55.52
+100	42.25	20.37	2.95	0.96	0.03	1.77	0.28	1.53	2.30	0.85	25.71
+150	52.99	23.67	3.55	1.06	0.03	1.56	0.41	1.94	2.40	0.94	10.46
+200	53.34	25.37	3.94	1.16	0.03	1.57	0.51	1.98	2.88	1.03	7.18
+270	52.43	26.06	4.09	1.27	0.03	1.57	0.15	2.00	3.54	1.09	6.77
+325	53.78	25.17	4.88	1.33	0.03	1.54	0.14	1.84	4.10	1.11	5.07
+400	53.25	25.09	4.91	1.35	0.03	1.56	0.11	1.86	4.26	1.14	5.44
-400	49.66	25.66	5.52	2.23	0.04	1.70	0.23	1.79	8.76	1.36	2.06
NPC As-Rec'd	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
Head	55.16	15.00	4.59	2.27	0.02	4.66	0.84	0.43	11.21	0.82	3.99
+65	35.91	11.96	3.27	1.38	0.01	1.98	0.15	0.12	5.85	0.55	37.83
+100	45.98	14.18	2.84	1.41	0.02	2.42	0.00	0.66	6.47	0.49	24.53
+150	56.21	16.27	3.60	1.63	0.02	2.34	0.09	0.51	8.00	0.51	9.80
+200	62.79	13.98	4.06	1.64	0.02	2.35	0.10	0.46	8.45	0.42	4.72
+270	62.24	14.68	3.73	1.66	0.02	2.64	0.14	0.39	9.41	0.49	3.60
+325	64.12	12.78	3.85	1.62	0.02	2.50	0.10	0.28	10.32	0.49	2.92
+400	62.73	13.90	4.15	1.77	0.02	2.86	0.03	0.25	9.94	0.52	2.82
-400	54.49	16.67	5.40	2.47	0.03	3.58	0.09	0.33	12.46	0.86	2.61

As-Received Fly Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

AEP As-Rec'd	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+100	<1.0	10.75	<1.0	106.0	<1.0	<1.0	<1.0	<1.0	<1.0	1260	<1.0
+150	<1.0	9.86	<1.0	104.1	<1.0	<1.0	<1.0	<1.0	<1.0	1413	<1.0
+200	<1.0	9.38	<1.0	128.9	<1.0	<1.0	<1.0	<1.0	<1.0	1606	<1.0
+270	<1.0	8.75	<1.0	102.2	<1.0	<1.0	<1.0	<1.0	<1.0	910.5	<1.0
+325	<1.0	11.63	<1.0	199.5	<1.0	<1.0	<1.0	<1.0	<1.0	2277	<1.0
+400	<1.0	9.18	<1.0	135.2	<1.0	<1.0	<1.0	<1.0	<1.0	1149	<1.0
-400	<1.0	12.61	<1.0	238.5	<1.0	<1.0	<1.0	<1.0	<1.0	2546	<1.0

AEP As-Rec'd	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

AEP As-Rec'd	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+100	<1.0	1289	<1.0	<1.0	<1.0	92.4	<1.0	<1.0	59.81	6.43	9.27
+150	<1.0	1451	<1.0	<1.0	<1.0	98.2	<1.0	<1.0	43.52	6.49	10.20
+200	<1.0	1668	<1.0	<1.0	<1.0	110.7	<1.0	<1.0	41.96	6.67	10.51
+270	<1.0	884.4	<1.0	<1.0	<1.0	62.93	<1.0	<1.0	24.74	6.23	8.69
+325	<1.0	2342	<1.0	<1.0	<1.0	155.3	<1.0	<1.0	43.30	7.13	11.23
+400	<1.0	1181	<1.0	<1.0	<1.0	84.15	<1.0	<1.0	59.57	6.44	10.18
-400	<1.0	2453	<1.0	<1.0	<1.0	154.9	<1.0	<1.0	40.57	7.29	13.11

AEP As-Rec'd	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+100	25.84	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	12.15	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	12.05	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	18.13	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	14.16	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	12.64	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	17.48	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

AEP As-Rec'd	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	11.66	<1.0		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.49	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.07	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	26.00	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	10.10	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.09	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	11.14	<1.0		

As-Received Fly Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

BGE As-Rec'd	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+100	<1.0	8.89	<1.0	61.94	<1.0	<1.0	<1.0	<1.0	<1.0	984.8	<1.0
+150	<1.0	9.78	<1.0	47.36	<1.0	<1.0	<1.0	<1.0	<1.0	643.1	<1.0
+200	<1.0	9.88	<1.0	72.68	<1.0	<1.0	<1.0	<1.0	<1.0	875.3	<1.0
+270	<1.0	10.53	<1.0	92.20	<1.0	<1.0	<1.0	<1.0	<1.0	1096	<1.0
+325	<1.0	9.93	<1.0	84.86	<1.0	<1.0	<1.0	<1.0	<1.0	1018	<1.0
+400	<1.0	12.46	<1.0	143.1	<1.0	<1.0	<1.0	<1.0	<1.0	2082	<1.0
-400	<1.0	8.54	<1.0	76.39	<1.0	<1.0	<1.0	<1.0	<1.0	800.2	<1.0

BGE As-Rec'd	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

BGE As-Rec'd	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+100	<1.0	1024	<1.0	<1.0	<1.0	108.1	<1.0	<1.0	188.4	8.10	12.41
+150	<1.0	683.9	<1.0	<1.0	<1.0	72.94	<1.0	<1.0	45.62	7.63	10.75
+200	<1.0	912.2	<1.0	<1.0	<1.0	93.61	<1.0	<1.0	51.07	8.02	12.87
+270	<1.0	1106	<1.0	<1.0	<1.0	107.2	<1.0	<1.0	114.8	8.21	13.58
+325	<1.0	1043	<1.0	<1.0	<1.0	100.9	<1.0	<1.0	85.17	8.12	12.41
+400	<1.0	2156	<1.0	<1.0	<1.0	197.2	<1.0	<1.0	61.01	9.74	19.63
-400	<1.0	856.0	<1.0	<1.0	<1.0	83.20	<1.0	<1.0	236.2	7.94	13.11

BGE As-Rec'd	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+100	22.26	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	13.08	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	13.30	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	13.47	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	12.03	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	15.84	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	16.07	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

BGE As-Rec'd	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	10.03	<1.0		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.11	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.36	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.90	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.51	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.98	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.62	<1.0		

As-Received Fly Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

NPC As-Rec'd	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+65	<1.0	8.12	<1.0	387.7	<1.0	<1.0	<1.0	<1.0	<1.0	5687	<1.0
+100	<1.0	8.00	<1.0	416.4	<1.0	<1.0	<1.0	<1.0	<1.0	6121	<1.0
+150	<1.0	8.70	<1.0	394.3	<1.0	<1.0	<1.0	<1.0	<1.0	6864	<1.0
+200	<1.0	9.61	<1.0	371.4	<1.0	<1.0	<1.0	<1.0	<1.0	6950	<1.0
+270	<1.0	8.46	<1.0	498.7	<1.0	<1.0	<1.0	<1.0	<1.0	8374	<1.0
+325	<1.0	9.19	<1.0	492.4	<1.0	<1.0	<1.0	<1.0	<1.0	8439	<1.0
+400	<1.0	9.33	<1.0	468.4	<1.0	<1.0	<1.0	<1.0	<1.0	8125	<1.0
-400	<1.0	10.07	<1.0	818.8	<1.0	<1.0	<1.0	<1.0	<1.0	11940	<1.0
NPC As-Rec'd	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
NPC As-Rec'd	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+65	<1.0	5560	<1.0	<1.0	<1.0	112.2	<1.0	<1.0	699.7	6.74	10.91
+100	<1.0	6273	<1.0	<1.0	<1.0	108.2	<1.0	<1.0	570.5	6.54	11.42
+150	<1.0	7086	<1.0	<1.0	<1.0	96.9	<1.0	<1.0	528.2	6.51	10.25
+200	<1.0	7128	<1.0	<1.0	<1.0	86.6	<1.0	<1.0	467.3	6.47	11.02
+270	<1.0	8670	<1.0	<1.0	<1.0	105.2	<1.0	<1.0	673.6	6.54	11.20
+325	<1.0	8629	<1.0	<1.0	<1.0	109.3	<1.0	<1.0	743.1	6.54	10.61
+400	<1.0	8289	<1.0	<1.0	<1.0	101.2	<1.0	<1.0	671.3	6.49	11.02
-400	<1.0	12590	<1.0	<1.0	<1.0	236.0	<1.0	<1.0	1912	6.89	17.01
NPC As-Rec'd	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+65	9.23	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+100	32.46	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	10.73	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	9.28	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	8.65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	11.95	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	13.46	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	20.55	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
NPC As-Rec'd	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.47	<1.0		
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	11.81	<1.0		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.72	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.66	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.06	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.84	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.10	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	16.34	<1.0		

As-Received Fly Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

DE As-Rec'd	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+65	<1.0	9.62	<1.0	336.3	<1.0	<1.0	<1.0	<1.0	<1.0	2390	<1.0
+100	<1.0	9.42	<1.0	356.2	<1.0	<1.0	<1.0	<1.0	<1.0	2294	<1.0
+150	<1.0	8.86	<1.0	409.6	<1.0	<1.0	<1.0	<1.0	<1.0	2645	<1.0
+200	<1.0	8.27	<1.0	452.6	<1.0	<1.0	<1.0	<1.0	<1.0	2938	<1.0
+270	<1.0	10.22	<1.0	564.2	<1.0	<1.0	<1.0	<1.0	<1.0	3788	<1.0
+325	<1.0	9.23	<1.0	639.1	<1.0	<1.0	<1.0	<1.0	<1.0	4245	<1.0
+400	<1.0	8.97	<1.0	656.7	<1.0	<1.0	<1.0	<1.0	<1.0	4636	<1.0
-400	<1.0	13.99	<1.0	1540	<1.0	<1.0	<1.0	<1.0	<1.0	11640	<1.0
DE As-Rec'd	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
DE As-Rec'd	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+65	<1.0	2446	<1.0	<1.0	<1.0	139.4	<1.0	<1.0	116.0	9.32	19.68
+100	<1.0	2274	<1.0	<1.0	<1.0	123.3	<1.0	<1.0	101.0	9.06	18.30
+150	<1.0	2761	<1.0	<1.0	<1.0	135.0	<1.0	<1.0	148.1	9.33	19.32
+200	<1.0	3016	<1.0	<1.0	<1.0	136.2	<1.0	<1.0	106.7	9.45	18.44
+270	<1.0	3856	<1.0	<1.0	<1.0	170.3	<1.0	<1.0	125.3	10.17	21.51
+325	<1.0	4404	<1.0	<1.0	<1.0	195.3	<1.0	<1.0	130.5	10.63	24.01
+400	<1.0	4789	<1.0	<1.0	<1.0	208.7	<1.0	<1.0	132.0	10.66	25.10
-400	<1.0	12350	<1.0	<1.0	<1.0	457.5	<1.0	<1.0	452.1	17.19	44.15
DE As-Rec'd	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+65	12.84	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+100	17.28	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	12.96	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	11.63	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	15.03	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	12.86	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	17.45	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	21.11	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
DE As-Rec'd	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.47	<1.0		
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	13.72	<1.0		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.56	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	13.42	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.91	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.99	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.68	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	17.84	<1.0		

As-Received Fly Ash Elemental Analysis by Size (ppm)

D.C. Popko, 24 Jun 96

CPC As-Rec'd	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+65	<1.0	9.67	<1.0	156.3	<1.0	<1.0	<1.0	<1.0	<1.0	2402	<1.0
+100	<1.0	7.62	<1.0	183.7	<1.0	<1.0	<1.0	<1.0	<1.0	2194	<1.0
+150	<1.0	9.80	<1.0	221.0	<1.0	<1.0	<1.0	<1.0	<1.0	2207	<1.0
+200	<1.0	8.76	<1.0	271.7	<1.0	<1.0	<1.0	<1.0	<1.0	2547	<1.0
+270	<1.0	7.98	<1.0	361.4	<1.0	<1.0	<1.0	<1.0	<1.0	3292	<1.0
+325	<1.0	8.58	<1.0	464.7	<1.0	<1.0	<1.0	<1.0	<1.0	4198	<1.0
+400	<1.0	10.65	<1.0	503.3	<1.0	<1.0	<1.0	<1.0	<1.0	4546	<1.0
-400	<1.0	14.58	<1.0	1110	<1.0	<1.0	<1.0	<1.0	<1.0	11650	<1.0

CPC As-Rec'd	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

CPC As-Rec'd	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+65	<1.0	2469	<1.0	<1.0	<1.0	181.4	<1.0	<1.0	89.61	9.26	11.88
+100	<1.0	2246	<1.0	<1.0	<1.0	165.2	<1.0	<1.0	68.68	8.97	12.55
+150	<1.0	2287	<1.0	<1.0	<1.0	140.2	<1.0	<1.0	60.27	9.06	11.92
+200	<1.0	2679	<1.0	<1.0	<1.0	147.9	<1.0	<1.0	57.56	9.44	13.22
+270	<1.0	3442	<1.0	<1.0	<1.0	175.3	<1.0	<1.0	68.52	10.09	14.42
+325	<1.0	4322	<1.0	<1.0	<1.0	225.0	<1.0	<1.0	79.45	11.10	16.79
+400	<1.0	4728	<1.0	<1.0	<1.0	236.8	<1.0	<1.0	85.91	11.61	16.05
-400	<1.0	12580	<1.0	<1.0	<1.0	572.2	<1.0	<1.0	276.3	19.04	32.34

CPC As-Rec'd	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+65	9.30	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+100	15.06	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	10.97	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	11.64	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	11.11	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	14.60	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	17.32	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	18.94	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

CPC As-Rec'd	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.55	<1.0		
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.68	<1.0		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.57	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.68	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.80	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.06	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.61	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	11.87	<1.0		

NEVADA POWER AS-RECEIVED ASH - SIZE DISTRIBUTION and LOI by Size							
Tyler Mesh		% Weight		% LOI		Distribution	
	Wt. (g)	individual	cumulative	individual	cumulative	individual	cumulative
+65	2.4	2.30	2.30	37.83	37.83	21.81	21.81
+100	1.2	1.15	3.45	24.53	33.40	7.07	28.88
+150	2.2	2.11	5.56	9.80	24.45	5.18	34.05
+200	4.2	4.02	9.58	4.72	16.16	4.76	38.82
+270	5.6	5.36	14.94	3.60	11.65	4.84	43.66
+325	4.6	4.41	19.35	2.92	9.66	3.23	46.88
+400	6.6	6.32	25.67	2.82	7.98	4.47	51.35
-400	77.6	74.33	100.0	2.61	3.99	48.65	100.0
head	104.4			3.99			

NEVADA POWER AS-RECEIVED ASH - MICROTRAC ANALYSIS		
Channel	Cumulative	Volume
62	100.0	2.6
44	97.4	9.1
31	88.3	11.4
22	76.9	12.0
16	64.9	11.7
11	53.3	10.2
7.8	43.1	9.6
5.5	33.5	7.5
3.9	26.0	9.2
2.8	16.7	9.6
1.9	7.2	4.0
1.4	3.2	2.5
0.9	0.7	0.7

BGE AS-RECEIVED ASH - SIZE DISTRIBUTION and LOI by Size							
Tyler Mesh		% Weight		% LOI		Distribution	
	Wt. (g)	individual	cumulative	individual	cumulative	individual	cumulative
+65							
+100	1.2	1.54	1.54	39.83	39.83	9.85	9.85
+150	2.2	2.82	4.36	19.06	26.39	8.64	18.48
+200	4.0	5.13	9.49	14.33	19.87	11.81	30.29
+270	4.6	5.90	15.38	10.23	16.18	9.69	39.98
+325	3.2	4.10	19.49	10.58	15.00	6.97	46.96
+400	8.4	10.77	30.26	6.76	12.07	11.70	58.65
-400	54.4	69.74	100.0	3.69	6.22	41.35	100.0
head	78.0			6.22			

BGE AS-RECEIVED ASH - MICROTRAC ANALYSIS		
Channel	Cumulative	Volume
62	100.0	3.8
44	96.2	12.1
31	84.1	15.7
22	68.4	16.4
16	52.0	14.9
11	37.1	11.5
7.8	25.6	8.8
5.5	16.7	6.1
3.9	10.6	4.4
2.8	6.2	3.9
1.9	2.3	1.5
1.4	0.8	0.8
0.9	0.0	0.0

AEP AS-RECEIVED ASH - SIZE DISTRIBUTION and LOI by Size							
Tyler Mesh		% Weight		% LOI		Distribution	
	Wt. (g)	individual	cumulative	individual	cumulative	individual	cumulative
+65	0.6	0.77	0.77	26.81	26.81	0.95	0.95
+100	1.4	1.79	2.55	56.99	47.94	4.70	5.64
+150	4.2	5.36	7.91	48.84	48.55	12.08	17.72
+200	7.8	9.95	17.86	43.11	45.52	19.80	37.52
+270	8.0	10.20	28.06	31.52	40.43	14.85	52.36
+325	3.8	4.85	32.91	32.66	39.28	7.31	59.67
+400	10.4	13.27	46.17	22.53	34.47	13.79	73.47
-400	42.2	53.83	100.0	10.68	21.66	26.53	100.0
head	78.4			21.66			

AEP AS-RECEIVED ASH - MICROTRAC ANALYSIS		
Channel	Cumulative	Volume
62	100.0	5.2
44	94.8	15.2
31	79.6	18.1
22	61.5	16.2
16	45.3	14.3
11	31.0	10.9
7.8	20.1	8.2
5.5	11.9	5.1
3.9	6.8	3.2
2.8	3.6	2.7
1.9	0.9	0.7
1.4	0.2	0.2
0.9	0.0	0.0

DETROIT EDISON-2 AS-RECEIVED ASH - SIZE DISTRIBUTION and LOI by Size							
Tyler Mesh		% Weight		% LOI		Distribution	
	Wt. (g)	individual	cumulative	individual	cumulative	individual	cumulative
+65	2.0	1.68	1.68	55.52	55.52	21.64	21.64
+100	1.8	1.51	3.18	25.71	41.4	9.02	30.66
+150	3.4	2.85	6.03	10.46	26.79	6.93	37.59
+200	5.2	4.36	10.39	7.18	18.57	7.28	44.87
+270	5.4	4.52	14.91	6.77	14.99	7.13	52.00
+325	7.8	6.53	21.44	5.07	11.97	7.71	59.7
+400	4.0	3.35	24.79	5.44	11.08	4.24	63.94
-400	89.8	75.21	100.00	2.06	4.3	36.06	100.00
head	119.4			4.30			

DETROIT EDISON-2 AS-RECEIVED ASH - MICROTRAC ANALYSIS		
Channel	Cumulative	Volume
88	100.0	0.2
62	99.8	3.7
44	96.0	9.5
31	86.5	11.6
22	74.9	12.6
16	62.3	12.4
11	49.9	11.1
7.8	38.8	10.3
5.5	28.5	8.3
3.9	20.2	7.9
2.8	12.4	7.3
1.9	5.1	3.0
1.4	2.1	1.7
0.9	0.4	0.4

Consumers Power Co. As-received Ash - Size Distribution and LOI by Size							
Tyler Mesh		% Weight		% LOI		Distribution	
	Wt. (g)	individual	cumulative	individual	cumulative	individual	cumulative
+65	0.0	0.00	0.00	0.0	0.00	0.0	0.00
+100	6.0	5.51	5.51	51.68	51.68	43.37	43.37
+150	4.2	3.86	9.38	13.10	35.79	7.70	51.07
+200	5.2	4.78	14.15	9.57	26.93	6.97	58.04
+270	3.8	3.49	17.65	7.37	23.06	3.92	61.96
+325	4.8	4.41	22.06	6.54	19.76	4.39	66.35
+400	4.6	4.23	26.29	5.16	17.41	3.32	69.68
-400	80.2	73.71	100.0	2.70	6.57	30.31	100.0
head	108.8			6.57			

Consumers Power Company As-received Ash - Microtrac Analysis		
Channel	Cumulative	Volume
62	100.0	1.6
44	98.4	7.4
31	91.1	11.4
22	79.6	13.4
16	66.3	15.1
11	51.2	14.3
7.8	36.9	12.3
5.5	24.6	8.9
3.9	15.7	6.0
2.8	9.7	5.6
1.9	4.1	2.4
1.4	1.6	1.4
0.9	0.2	0.2

Screen Analysis for Holyoke B2			
Mesh	weight, grams	weight %	cumulative wt % retained
+10	5.05	2.49	2.49
-10 +35	11.67	5.76	8.25
-35 +48	37.61	18.56	26.81
-48 +65	45.35	22.38	49.19
-65 +100	36.04	17.78	66.97
-100 +150	29.90	14.75	81.72
-150 +200	17.48	8.62	90.34
-200 +270	12.39	6.11	96.45
-270	7.18	3.54	99.99
Total	202.67		
Head LOI %	16.23		

Screen Analysis for Holyoke A2			
Mesh	weight, grams	weight %	cumulative wt % retained
+10			
-10 +35	74.36	21.88	21.88
-35 +48	71.36	21.00	42.88
-48 +65	62.05	18.26	61.14
-65 +100	42.54	12.52	73.66
-100 +150	28.57	8.41	82.07
-150 +200	23.20	6.83	88.90
-200 +270	24.68	7.26	96.16
-270	13.13	3.86	100.02
Total	339.89		
Head LOI %	21.50		

Screen Analysis for Newcastle 900			
Mesh	weight, grams	weight %	cumulative wt % retained
+10			
-10 +35			
-35 +48	49.95	17.30	17.30
-48 +65	63.21	21.89	39.19
-65 +100	50.37	17.44	56.63
-100 +150	44.48	15.40	72.03
-150 +200	37.86	13.11	85.14
-200 +270	29.78	10.31	95.45
-270	13.13	4.55	100.0
Total	288.78		
Head LOI %	25.39		

Screen Analysis for Newcastle 500			
Mesh	weight, grams	weight %	cumulative wt % retained
+10			
-10 +35			
-35 +48			
-48 +65	60.66	26.02	26.02
-65 +100	59.65	25.58	51.59
-100 +150	47.60	20.41	72.00
-150 +200	31.01	13.30	85.30
-200 +270	25.73	11.03	96.33
-270	8.52	3.65	99.98
Total	233.17		
Head LOI %	17.07		

Appendix 2

Chemical Analysis by Size of Clean Ash Samples

Clean Fly Ash Chemical Analysis by Size

D.C. Popko, 23 Apr 96

AEP Clean	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
+150	53.52	25.14	4.47	1.11	0.02	0.95	0.01	3.15	1.13	0.81	8.69
+200	57.78	25.87	4.28	1.05	0.02	0.99	0.09	3.07	1.01	0.90	3.95
+270	59.11	26.82	4.49	1.03	0.02	0.86	0.06	3.09	0.96	0.98	1.59
+325	58.62	27.21	5.19	1.03	0.02	0.98	0.02	3.05	0.75	1.04	1.08
+400	59.06	27.68	4.82	1.03	0.02	0.85	0.06	3.14	0.74	1.09	0.53
-400	55.25	29.55	6.02	1.13	0.02	1.14	0.04	2.96	1.30	1.26	0.34
BGE Clean	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
+150	59.11	26.08	2.98	0.89	0.01	0.63	0.05	2.39	0.93	1.08	4.84
+200	59.12	27.90	2.72	0.99	0.01	0.83	0.04	2.57	0.68	1.27	2.87
+270	59.98	28.08	2.77	0.97	0.01	0.56	0.03	2.43	0.64	1.29	2.25
+325	59.21	28.93	2.87	0.99	0.01	0.75	0.03	2.32	0.79	1.38	1.72
+400	59.26	29.00	2.99	0.96	0.01	0.98	0.01	2.45	0.88	1.39	1.08
-400	58.35	28.72	3.74	1.05	0.01	1.02	0.00	2.30	1.26	1.57	0.97
CPC Clean	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
+150	56.71	29.23	5.37	0.99	0.02	0.94	0.04	1.86	1.93	1.11	0.81
+200	56.32	27.95	7.08	1.03	0.03	1.02	0.03	1.81	2.05	1.24	0.44
+270	55.30	28.40	7.44	1.09	0.03	1.07	0.01	1.84	2.33	1.25	0.26
+325	55.61	28.16	7.20	1.12	0.01	1.03	0.02	1.79	2.68	1.27	0.12
+400	55.49	27.51	7.65	1.23	0.10	1.19	0.00	1.76	2.79	1.26	0.12
-400	51.43	27.21	7.35	1.86	0.00	1.37	0.09	2.03	5.09	1.47	1.11
DE#2 Clean	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
+65	33.25	16.71	2.81	1.13	0.02	0.53	0.10	1.10	3.95	0.92	38.47
+100	56.60	25.56	3.06	1.26	0.02	0.41	0.00	2.36	2.82	1.02	5.89
+150	58.36	27.30	2.99	1.32	0.02	0.53	0.03	2.48	2.95	1.10	1.92
+200	58.73	27.34	2.94	1.33	0.02	0.80	0.00	2.57	3.25	1.13	0.90
+270	57.91	27.53	3.15	1.48	0.02	0.52	0.04	2.44	3.83	1.24	0.85
+325	57.83	26.41	3.27	1.59	0.02	0.64	0.10	2.20	4.87	1.25	0.83
+400	57.89	26.21	3.37	1.62	0.02	0.85	0.00	2.14	4.99	1.26	0.65
-400	51.44	25.72	4.52	2.47	0.02	0.96	0.16	2.01	9.12	1.42	1.16
NPC Clean	SiO₂	Al₂O₃	Fe₂O₃	MgO	MnO	Na₂O	P₂O₅	K₂O	CaO	TiO₂	LOI
+65	44.36	12.69	3.70	1.59	0.02	2.19	0.00	0.37	12.75	0.62	20.71
+100	44.52	13.77	2.91	1.53	0.02	2.26	0.01	0.44	14.12	0.56	18.87
+150	56.62	15.54	3.14	1.53	0.02	2.40	0.00	0.66	9.13	0.53	9.44
+200	62.46	15.98	2.42	1.39	0.03	2.69	0.02	0.58	7.05	0.54	5.85
+270	66.93	14.71	2.35	1.31	0.01	2.54	(0.04)	0.54	6.23	0.52	3.88
+325	67.32	14.09	2.54	1.42	0.02	2.75	0.00	0.48	6.70	0.55	3.14
+400	68.61	13.93	2.57	1.44	0.02	2.60	0.02	0.41	6.26	0.53	2.59
-400	54.37	17.03	4.58	2.48	0.03	3.84	0.10	0.57	10.51	0.92	4.56

Clean Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

AEP Clean	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+150	<1.0	11.75	<1.0	115.8	<1.0	<1.0	<1.0	<1.0	<1.0	1006	<1.0
+200	<1.0	11.3	<1.0	134.1	<1.0	<1.0	<1.0	<1.0	<1.0	758.1	<1.0
+270	<1.0	9.29	<1.0	155.6	<1.0	<1.0	<1.0	<1.0	<1.0	776.8	<1.0
+325	<1.0	11.95	<1.0	194.3	<1.0	<1.0	<1.0	<1.0	<1.0	932.3	<1.0
+400	<1.0	11.95	<1.0	195.2	<1.0	<1.0	<1.0	<1.0	<1.0	1017	<1.0
-400	<1.0	15.42	<1.0	398.6	<1.0	<1.0	<1.0	<1.0	<1.0	6332	<1.0

AEP Clean	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

AEP Clean	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+150	<1.0	1051	<1.0	<1.0	<1.0	58.67	<1.0	<1.0	44.36	6.95	9.58
+200	<1.0	772.1	<1.0	<1.0	<1.0	65.27	<1.0	<1.0	26.08	7.07	10.17
+270	<1.0	789.6	<1.0	<1.0	<1.0	64.55	<1.0	<1.0	23.93	7.08	9.60
+325	<1.0	937.4	<1.0	<1.0	<1.0	75.11	<1.0	<1.0	39.62	7.27	10.88
+400	<1.0	1033	<1.0	<1.0	<1.0	81.23	<1.0	<1.0	28.45	7.25	11.35
-400	<1.0	3707	<1.0	<1.0	<1.0	241.3	<1.0	<1.0	38.02	9.42	17.88

AEP Clean	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+150	29.63	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	10.39	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	10.46	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	15.35	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	12.73	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	16.18	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

AEP Clean	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	13.14	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.61	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.63	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.88	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.49	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	10.61	<1.0		

Clean Fly Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

BGE Clean	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+150	<1.0	23.96	<1.0	55.09	<1.0	<1.0	<1.0	<1.0	<1.0	671.9	<1.0
+200	<1.0	11.15	<1.0	49.72	<1.0	<1.0	<1.0	<1.0	<1.0	426	<1.0
+270	<1.0	12.08	<1.0	53.04	<1.0	<1.0	<1.0	<1.0	<1.0	449.1	<1.0
+325	<1.0	11.23	<1.0	63.55	<1.0	<1.0	<1.0	<1.0	<1.0	538.3	<1.0
+400	<1.0	12.18	<1.0	61.48	<1.0	<1.0	<1.0	<1.0	<1.0	535.1	<1.0
-400	<1.0	12.30	<1.0	109.58	<1.0	<1.0	<1.0	<1.0	<1.0	1475.4	<1.0

BGE Clean	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

BGE Clean	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+150	<1.0	683.8	<1.0	<1.0	<1.0	53.71	<1.0	<1.0	50.64	16.86	20.10
+200	<1.0	429.7	<1.0	<1.0	<1.0	42.98	<1.0	<1.0	19.56	7.38	10.18
+270	<1.0	453.3	<1.0	<1.0	<1.0	45.13	<1.0	<1.0	18.38	7.41	10.11
+325	<1.0	534.9	<1.0	<1.0	<1.0	53.19	<1.0	<1.0	18.24	7.50	10.46
+400	<1.0	534.6	<1.0	<1.0	<1.0	52.94	<1.0	<1.0	16.26	7.48	10.11
-400	<1.0	1439.6	<1.0	<1.0	<1.0	132.4	<1.0	<1.0	28.15	8.88	15.07

BGE Clean	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+150	22.59	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	9.00	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	8.62	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	9.63	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	8.28	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	16.81	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

BGE Clean	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	18.38	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.37	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.74	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.24	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.45	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	9.73	<1.0		

Clean Fly Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

NPC Clean	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+65	<1.0	16.75	<1.0	571.1	<1.0	<1.0	<1.0	<1.0	<1.0	12440	<1.0
+100	<1.0	10.98	<1.0	433.3	<1.0	<1.0	<1.0	<1.0	<1.0	4847	<1.0
+150	<1.0	35.48	<1.0	541.8	<1.0	<1.0	<1.0	<1.0	<1.0	7283.5	<1.0
+270	<1.0	10.22	<1.0	418.4	<1.0	<1.0	<1.0	<1.0	<1.0	4635	<1.0
+325	<1.0	11.68	<1.0	473.2	<1.0	<1.0	<1.0	<1.0	<1.0	5063	<1.0
+400	<1.0	25.81	<1.0	352.1	<1.0	<1.0	<1.0	<1.0	<1.0	4097.5	<1.0
-400	<1.0	10.95	<1.0	724.6	<1.0	<1.0	<1.0	<1.0	<1.0	8719	<1.0

NPC Clean	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

NPC Clean	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+65	<1.0	13154	<1.0	<1.0	<1.0	167.8	<1.0	<1.0	1588	10.7	19.03
+100	<1.0	5220	<1.0	<1.0	<1.0	110.5	<1.0	<1.0	701.5	6.54	11.64
+150	<1.0	7919	<1.0	<1.0	<1.0	148.6	<1.0	<1.0	1095	24.67	35.21
+270	<1.0	4927	<1.0	<1.0	<1.0	107.0	<1.0	<1.0	675.4	6.58	10.88
+325	<1.0	5426	<1.0	<1.0	<1.0	117.2	<1.0	<1.0	777.7	6.75	11.75
+400	<1.0	4305	<1.0	<1.0	<1.0	109.3	<1.0	<1.0	655.7	18.45	25.14
-400	<1.0	8942	<1.0	<1.0	<1.0	254.8	<1.0	<1.0	1575	6.79	18.05

NPC Clean	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+65	218.23	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+100	12.96	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+150	30.56	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	12.57	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	11.85	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	22.95	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	14.97	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

NPC Clean	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+65	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	13.14	<1.0		
+100	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.82	<1.0		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	25.44	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.81	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.71	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	18.63	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	10.92	<1.0		

Clean Fly Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

DE Clean	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+150	<1.0	10.26	<1.0	391.2	<1.0	<1.0	<1.0	<1.0	<1.0	2619	<1.0
+200	<1.0	11.44	<1.0	439.5	<1.0	<1.0	<1.0	<1.0	<1.0	2859	<1.0
+270	<1.0	12.30	<1.0	601.1	<1.0	<1.0	<1.0	<1.0	<1.0	3973	<1.0
+325	<1.0	11.88	<1.0	723.9	<1.0	<1.0	<1.0	<1.0	<1.0	4820	<1.0
+400	<1.0	11.31	<1.0	418.6	<1.0	<1.0	<1.0	<1.0	<1.0	2902	<1.0
-400	<1.0	17.67	<1.0	1522	<1.0	<1.0	<1.0	<1.0	<1.0	11020	<1.0

DE Clean	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

DE Clean	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+150	<1.0	2641	<1.0	<1.0	<1.0	106.7	<1.0	<1.0	8.84	8.02	15.14
+200	<1.0	2899	<1.0	<1.0	<1.0	123.7	<1.0	<1.0	87.15	8.31	16.74
+270	<1.0	4057	<1.0	<1.0	<1.0	170.5	<1.0	<1.0	123.1	9.26	20.07
+325	<1.0	4938	<1.0	<1.0	<1.0	205.9	<1.0	<1.0	154.1	9.94	23.66
+400	<1.0	2907	<1.0	<1.0	<1.0	124.0	<1.0	<1.0	81.33	8.29	16.28
-400	<1.0	11320	<1.0	<1.0	<1.0	462.5	<1.0	<1.0	416.5	17.23	43.19

DE Clean	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+150	11.40	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	11.12	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	10.69	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+325	12.08	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	15.31	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	23.57	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

DE Clean	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.33	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	7.71	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.29	<1.0		
+325	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.93	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.48	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	14.72	<1.0		

Clean Fly Ash Elemental Analysis by Size (ppm)
D.C. Popko, 24 Jun 96

CPC Clean	P	As	Ag	Ba	Cd	Cr	Pb	Se	Bi	Ce	Dy
+150	<1.0	11.49	<1.0	221.8	<1.0	<1.0	<1.0	<1.0	<1.0	2020.9	<1.0
+200	<1.0	10.10	<1.0	271.4	<1.0	<1.0	<1.0	<1.0	<1.0	2393	<1.0
+270	<1.0	20.32	<1.0	367.3	<1.0	<1.0	<1.0	<1.0	<1.0	3122.6	<1.0
+400	<1.0	65.53	<1.0	520.9	<1.0	<1.0	<1.0	<1.0	<1.0	4606.2	<1.0
-400	<1.0	14.32	<1.0	1164	<1.0	<1.0	<1.0	<1.0	<1.0	12060	<1.0

CPC Clean	Er	Eu	Ga	Gd	Hg	Ho	In	La	Lu	Pr	Sc
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

CPC Clean	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co
+150	<1.0	2061.6	<1.0	<1.0	<1.0	102.8	<1.0	<1.0	83.48	10.27	14.64
+200	<1.0	2401	<1.0	<1.0	<1.0	113.7	<1.0	<1.0	67.14	8.27	14.77
+270	<1.0	3089.2	<1.0	<1.0	<1.0	151.1	<1.0	<1.0	94.52	15.74	25.12
+400	<1.0	4653.2	<1.0	<1.0	<1.0	242.3	<1.0	<1.0	169.4	49.49	65.75
-400	<1.0	12170	<1.0	<1.0	<1.0	551.9	<1.0	<1.0	240.4	16.64	32.04

CPC Clean	Cu	Ge	Hf	Ir	Li	Nb	Ni	Os	Pd	Pt	Re
+150	11.18	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+200	8.89	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+270	15.57	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
+400	49.42	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
-400	18.28	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0

CPC Clean	Rh	Ru	Sb	Sn	Ta	V	W	Zn	Zr		
+150	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	8.95	<1.0		
+200	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	6.95	<1.0		
+270	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	13.46	<1.0		
+400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	43.28	<1.0		
-400	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	11.82	<1.0		

AEP Clean Ash

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	0.0	0.00	0.00	88	100.0	0.1
				62	99.9	4.3
+150	0.6	1.36	1.36	44	95.5	12.1
				31	83.5	14.7
+200	2.4	5.45	6.82	22	68.8	14.3
				16	54.5	13.9
+270	2.8	6.36	13.18	11	40.6	11.8
				7.8	28.8	9.4
+325	4.0	9.09	22.27	5.5	19.4	6.6
				3.9	12.7	5.4
+400	3.2	7.27	29.55	2.8	7.4	4.8
				1.9	2.6	1.7
-400	31.0	70.45	100.0	1.4	0.8	0.8
				0.9	0.0	0

AEP Cenospheres

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	2.2	5.73	5.73	88	100.0	0.2
				62	99.8	7.9
+150	10.8	28.13	33.85	44	91.8	23.8
				31	68.1	24.7
+200	11.0	28.65	62.50	22	43.4	13.3
				16	30.1	8.7
+270	6.8	17.71	80.21	11	21.4	7.1
				7.8	14.3	5.5
+325	4.0	10.42	90.63	5.5	8.7	3.7
				3.9	5.0	2.5
+400	1.2	3.13	93.75	2.8	2.5	2.0
				1.9	0.4	0.4
-400	2.4	6.25	100.0	1.4	0.0	0.0
				0.9	0.0	0.0

AEP Magnetics

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	0.0	0.00	0.00	88	100.0	2.8
				62	97.2	10.7
+150	0.6	0.96	0.96	44	86.5	21.4
				31	65.1	22.6
+200	2.6	4.18	5.14	22	42.5	17.1
				16	25.4	11.7
+270	5.2	8.36	13.50	11	13.8	6.9
				7.8	6.9	3.9
+325	9.2	14.79	28.30	5.5	3.0	2.1
				3.9	0.9	0.8
+400	6.8	10.93	39.23	2.8	0.1	0.1
				1.9	0.0	0.0
-400	37.8	60.77	100.0	1.4	0.0	0.0
				0.9	0.0	0.0

AEP Carbon

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	0.0	0.00	0.00	88	100.0	1.6
				62	98.4	8.9
+150	1.4	4.29	4.29	44	89.5	19.1
				31	70.4	19.4
+200	5.6	17.18	21.47	22	50.9	14.4
				16	36.5	11.3
+270	5.4	16.56	38.04	11	25.3	7.9
				7.8	17.4	6.0
+325	5.4	16.56	54.68	5.5	11.4	4.6
				3.9	6.8	3.7
+400	3.0	9.20	63.80	2.8	3.1	2.7
				1.9	0.5	0.5
-400	11.8	36.20	100.0	1.4	0.0	0.0
				0.9	0.0	0.0

BGE Clean Ash

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	0.0	0.00	0.00	88	100.0	0.0
+150	0.6	1.20	1.20	62	100.0	4.5
+200	2.4	4.82	6.02	44	95.5	13.6
+270	3.0	6.02	12.05	31	81.9	18.3
+325	5.0	10.04	22.09	22	63.6	18.4
+400	3.8	7.63	29.72	16	45.2	16.2
-400	35.0	70.28	100.0	11	29.1	11.1
				7.8	18.0	6.8
				5.5	11.1	4.1
				3.9	7.1	3.1
				2.8	4.0	2.8
				1.9	1.2	0.9
				1.4	0.3	0.3
				0.9	0.0	0.0

BGE Cenospheres

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	1.8	5.39	5.39	88	100.0	0.0
+150	9.2	27.54	32.93	62	100.0	4.5
+200	10.8	32.34	65.27	44	95.5	17.4
+270	6.2	18.56	83.83	31	78.2	19.6
+325	2.8	8.38	92.22	22	58.6	12.7
+400	0.8	2.40	94.61	16	45.9	11.2
-400	1.8	5.39	100.0	11	34.7	10.9
				7.8	23.8	8.4
				5.5	15.4	5.5
				3.9	9.9	4.6
				2.8	5.4	3.9
				1.9	1.4	1.1
				1.4	0.3	0.3
				0.9	0.0	0.0

BGE Magnetics

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	2.6	2.03	2.03	88	99.7	3.1
+150	4.0	3.13	5.16	62	96.5	9.5
+200	9.0	7.04	12.21	44	87.1	19.7
+270	14.6	11.42	23.63	31	67.4	21.8
+325	21.2	16.59	40.22	22	45.6	17.0
+400	13.6	10.64	50.86	16	28.5	12.1
-400	62.8	49.14	100.0	11	16.4	7.4
				7.8	9.0	4.6
				5.5	4.4	2.5
				3.9	1.9	1.2
				2.8	0.7	0.7
				1.9	0.0	0.0
				1.4	0.0	0.0
				0.9	0.0	0.0

BGE Carbon

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	0.0	0.00	0.00	88	100.0	0.0
+150	0.8	1.52	1.52	62	100.0	1.3
+200	2.6	4.92	6.44	44	98.7	5.9
+270	2.4	4.55	10.98	31	92.8	7.6
+325	3.4	6.44	17.42	22	85.2	8.6
+400	2.6	4.92	22.35	16	76.6	10.8
-400	41.0	77.65	100.0	11	65.8	11.9
				7.8	53.9	13.5
				5.5	40.4	12.0
				3.9	28.5	11.5
				2.8	17.0	10.3
				1.9	6.7	3.9
				1.4	2.8	2.3
				0.9	0.5	0.5

NPC Clean Ash

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
				88	100.0	0.0
+100	0.4	0.75	0.75	62	100.0	3.2
				44	96.8	9.7
+150	0.6	1.12	1.87	31	87.1	12.2
				22	74.9	12.1
+200	3.4	6.34	8.21	16	62.8	12.2
				11	50.6	10.6
+270	6.2	11.57	19.78	7.8	40.0	9.4
				5.5	30.5	7.6
+325	7.2	13.43	33.21	3.9	22.9	8.4
				2.8	14.5	8.4
+400	4.6	8.58	41.79	1.9	6.1	3.5
				1.4	2.6	2.1
-400	31.2	58.21	100.0	0.9	0.5	0.5

NPC Cenospheres

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
				88	100.0	0.0
+100	4.4	12.94	12.94	62	100.0	0.7
				44	99.3	6.2
+150	7.6	22.35	35.29	31	93.1	9.4
				22	83.7	10.6
+200	9.0	26.47	61.76	16	73.1	13.7
				11	59.4	15.0
+270	5.4	15.88	77.65	7.8	44.4	13.3
				5.5	31.1	10.0
+325	2.2	6.47	84.12	3.9	21.1	8.6
				2.8	12.4	7.7
+400	0.6	1.76	85.88	1.9	4.8	2.9
				1.4	1.8	1.6
-400	4.8	14.12	100.0	0.9	0.2	0.2

NPC Magnetics

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	1.0	2.01	2.01	88	100.0	0.0
+150	1.6	3.21	5.22	62	100.0	3.2
+200	3.0	6.02	11.24	44	96.8	13.6
+270	4.0	8.03	19.28	31	83.2	19.6
+325	6.4	12.85	32.13	22	63.6	18.4
+400	5.0	10.04	42.17	16	45.2	15.2
-400	28.8	57.83	100.0	11	30.0	11.0
				7.8	19.1	7.8
				5.5	11.3	5.4
				3.9	5.9	3.4
				2.8	2.5	2.2
				1.9	0.3	0.3
				1.4	0.0	0.0
				0.9	0.0	0.0

NPC Carbon

Sieve Analysis				Microtrac Analysis of -400 mesh fraction		
<u>Tyler Mesh</u>	<u>Weight (grams)</u>	<u>Individual Wt% Retained</u>	<u>Cumulative Wt% Retained</u>	<u>Channel (microns)</u>	<u>Cumulative % Passing</u>	<u>Volume % Passing</u>
+100	0.2	0.56	0.56	88	100.0	0.9
+150	1.0	2.81	3.37	62	99.1	3.1
+200	2.4	6.74	10.11	44	96.0	7.7
+270	2.8	7.87	17.98	31	88.3	10.3
+325	4.2	11.80	29.78	22	78.0	10.8
+400	2.2	6.18	35.96	16	67.2	11.2
-400	22.8	64.04	100.0	11	56.0	10.4
				7.8	45.6	9.7
				5.5	36.0	8.5
				3.9	27.4	10.7
				2.8	16.8	10.1
				1.9	6.7	3.9
				1.4	2.8	2.3
				0.9	0.5	0.5

Appendix 3

Water Analyses

Chemical Analysis Pilot Plant Water, AEP Ash
D.C. Popko
17 Jan 96

Elemental Analysis of Water (Filtrate) Associated with Each Sample																						
Sample	Si	Al	Ca	Mg	Na	P	K	As	Ag	Ba	Cd	Cr	Pb	Se	Fe	Bi	Ce	Dy	Er	Eu	Ga	Gd
Carbon Concentrate	5.03	0.51	642	bdl	13.6	bdl	9.04	bdl	0.01	0.17	bdl	0.01	bdl	0.25	0.01	0.15	1.31	0.01	0.01	0.02	0.01	0.01
Clean Ash	bdl	2.4	116	bdl	20.8	bdl	26.1	bdl	0.02	0.19	bdl	0.01	bdl	0.09	0.07	0.11	3.33	0.01	0.01	0.01	0.05	0.01
Process Water	4.15	0.55	43.3	7.83	10	bdl	1.78	bdl	0.02	0.05	bdl	bdl	bdl	bdl	0.03	0.08	0.15	0.01	0.01	0.01	0.04	0.01
	Hg	Ho	In	La	Lu	Pr	Sc	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co	Cu	Ge	Hf	Ir
Carbon Concentrate	bdl	0.02	0.01	0.04	0.01	0.01	0.02	0.04	1.37	0.01	0.01	0.1	0.01	0.01	0.02	0.01	bdl	0.01	0.01	0.01	0.01	0.01
Clean Ash	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.01	3.53	0.02	0.01	0.15	0.01	0.01	0.06	0.01	bdl	0.03	0.01	0.01	0.01	0.01
Process Water	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.16	0.01	0.01	0.06	0.01	0.01	0.03	0.01	bdl	0.01	0.01	0.01	0.01	0.01
	Li	Mn	Nb	Ni	Os	Pd	Pt	Re	Rh	Ru	Sb	Sn	Ta	Ti	V	W	Zn	Zr				
Carbon Concentrate	0.03	bdl	0.04	0.01	0.06	0.01	0.03	0.05	0.16	0.02	0.01	0.01	0.02	0.01	0.14	0.29	0.39	0.01				
Clean Ash	0.66	bdl	0.05	0.16	0.01	0.01	0.06	0.06	0.13	0.01	0.01	0.12	0.04	0.01	0.07	0.28	3.04	0.01				
Process Water	0.01	0.07	0.02	0.01	0.01	0.01	0.01	0.01	0.09	0.01	0.01	0.13	0.01	bdl	0.03	0.26	0.01	bdl				
bdl = below detection limit																						

Fly Ash
Chemical Analysis ICP
D.C. Popko

Elemental Analysis									
	Si	Al	Fe	Mg	Ca	Na	K	P	LOI
AEP Magnetics	5.434	4.398	51.91	0.229	0.579	0.661	1.37	0.021	-1.4
AEP Clean Ash	25.92	16.48	4.859	0.667	0.845	0.83	3.079	0.046	0.91
AEP Cenospheres	24.74	16.38	3.243	0.831	0.489	0.836	4.412	0.014	1.95
AEP Carbon	2.369	2.334	0.911	0.018	0.417	0.604	0.867	bdl	68.62
BGE Feed	23.61	15	2.953	0.476	0.895	0.784	2.635	0.043	6.53
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O ₃	K ₂ O	P ₂ O ₅	LOI
AEP Magnetics	11.62	8.31	74.22	0.38	0.81	0.891	1.65	0.048	-1.4
AEP Clean Ash	55.44	31.14	6.947	1.106	1.182	1.119	3.709	0.105	0.91
AEP Cenospheres	52.92	30.95	4.637	1.378	0.684	1.127	5.315	0.032	1.95
AEP Carbon	5.067	4.41	1.302	0.03	0.583	0.814	1.045	bdl	68.62
BGE Feed	50.5	28.34	4.222	0.789	1.252	1.057	3.174	0.099	6.53
<i>bdl = below detection limits</i>									

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APHA-AWWA-WPCF

Fly-ash Waters, Pilot Plant AEP ash

D.C. Popko

7 Feb 96

	Total Residue Dried at 103-105°C			Total Filterable Residue Dried at 180°C			Total Filterable Residue Dried at 103-105°C		
	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)
Sample	<u>Dish (mg)</u>	<u>Residue (mg)</u>	<u>(mg/L)</u>	<u>Dish (mg)</u>	<u>Residue (mg)</u>	<u>Residue (mg/L)</u>	<u>Dish (mg)</u>	<u>Residue (mg)</u>	<u>Residue (mg/L)</u>
Carbon									
Concentrate	50,655.90	50,662.80	276.00	55,573.20	55,576.60	226.67	55,569.80	55,576.60	272.00
Clean Ash	49,621.60	49,632.00	416.00	70,820.00	70,825.30	353.33	70,814.50	70,824.20	388.00
Process Water	55,652.10	55,653.40	52.00	55,921.60	55,922.30	46.67	55,921.00	55,922.30	52.00

	Total Non-Filterable Residue			Total Volatile and Fixed Residue at 550°C				
	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg) Before Ignition	Weight of Dish + Residue (mg) After Ignition	Volatile Residue (mg/L)	Fixed Residue (mg/L)
Sample	<u>Dish (mg)</u>	<u>Residue (mg)</u>	<u>Residue (mg/L)</u>	<u>Dish (mg)</u>	<u>Before Ignition</u>	<u>After Ignition</u>	<u>(mg/L)</u>	<u>(mg/L)</u>
Carbon								
Concentrate	146.4	146.6	2	50,655.90	50,662.80	50,660.10	108.00	168.00
Clean Ash	147.6	147.7	01	49,621.60	49,632.00	49,628.80	128.00	288.00
Process Water	146.2	146.2	0	55,652.10	55,653.40	55,653.10	12.00	40.00

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APHA-AWWA-WPCF
Fly Ash Water, Pilot Plant AEP Ash
D.C. Popko
7 Feb 96

Sample	Mg (ppm)	Ca (ppm)	Hardness
Carbon Concentrate	0.00	64.2	160.31
Clean Ash	0.00	116.0	289.65
Process Water	7.83	43.3	140.36

Chemical Analysis Pilot Plant Water, Detroit Edison Ash
D.C. Popko
17 Jan 96

Elemental Analysis of Water (Filtrate) Associated with Each Sample																						
Sample	Si	Al	Ca	Mg	Na	P	K	As	Ag	Ba	Cd	Cr	Pb	Se	Fe	Bi	Ce	Dy	Er	Eu	Ga	Gd
Carbon Concentrate	0.01	8.72	90.7	bdl	20.7	bdl	7.41	bdl	0.01	0.17	bdl	0.17	bdl	0.45	bdl	0.09	1.49	bdl	bdl	bdl	bdl	bdl
Clean Ash	bdl	41.7	199	bdl	40.2	bdl	20.4	bdl	0.01	0.1	bdl	0.6	bdl	0.97	bdl	0.14	4.93	0.01	bdl	bdl	0.05	bdl
Process Water	4.13	bdl	42.6	8.03	10.3	bdl	0.02	bdl	0.01	0.06	bdl	bdl	bdl	bdl	bdl	0.08	0.17	bdl	bdl	bdl	bdl	bdl
	Hg	Ho	In	La	Lu	Pr	Sc	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co	Cu	Ge	Hf	Ir
Carbon Concentrate	bdl	bdl	bdl	0.02	bdl	bdl	bdl	bdl	1.5	bdl	bdl	0.1	bdl	bdl	bdl	bdl	bdl	0.01	bdl	0.01	bdl	0.05
Clean Ash	bdl	bdl	bdl	0.02	bdl	0.19	bdl	bdl	4.94	0.09	bdl	0.19	bdl	bdl	bdl	bdl	bdl	0.01	bdl	bdl	bdl	0.08
Process Water	bdl	bdl	bdl	0.02	bdl	bdl	bdl	bdl	0.17	0.03	bdl	0.05	bdl	bdl	bdl	2	bdl	bdl	bdl	bdl	bdl	0.07
	Li	Mn	Nb	Ni	Os	Pd	Pt	Re	Rh	Ru	Sb	Sn	Ta	Ti	V	W	Zn	Zr				
Carbon Concentrate	0.23	bdl	0.1	0.03	0303	bdl	0.04	0.01	0.04	bdl	bdl	0.08	bdl	bdl	bdl	bdl	0.9	0.01				
Clean Ash	0.06	bdl	0.09	0.03	0.04	bdl	0.07	0.09	0.1	bdl	bdl	bdl	bdl	bdl	bdl	bdl	0.01	0.01				
Process Water	bdl	0.06	0.07	0.03	0.06	bdl	0.07	bdl	0.09	bdl	bdl	0.01	bdl	bdl	bdl	bdl	0.12	bdl				
bdl = below detection limit																						

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APHA-AWWA-WPCF

Fly-ash Waters, Detroit Edison ash

D.C. Popko

20 Mar 96

	Total Residue Dried at 103-105°C			Total Filterable Residue Dried at 180°C			Total Filterable Residue Dried at 103-105°C		
	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)
Sample									
Carbon									
Concentrate	30,991.00	31,004.90	556.00	27,470.20	27,482.40	488.00	27,470.20	27,483.50	532.00
Clean Ash	30,830.50	30,864.50	1,360.00	25,719.00	25,750.50	1,260.00	25,719.00	25,751.80	1,312.00
Process Water	31,144.80	31,146.20	56.00	27,484.40	27,485.30	36.00	27,484.40	27,485.70	52.00

	Total Non-Filterable Residue			Total Volatile and Fixed Residue at 550°C				
	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg) Before Ignition	Weight of Dish + Residue (mg) After Ignition	Volatile Residue (mg/L)	Fixed Residue (mg/L)
Sample								
Carbon								
Concentrate	145.5	146.8	13	30,991.00	31,004.90	31,004.10	32.00	524.00
Clean Ash	146.5	147	5	30,830.50	30,864.50	30,859.50	200.00	1,160.00
Process Water	146.4	146.4	0	31,144.80	31,146.20	31,146.00	8.00	48.00

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APHA-AWWA-WPCF

Fly Ash Water, Detroit Edison Ash

D.C. Popko

23 Mar 96

Sample	Mg (ppm)	Ca (ppm)	Hardness
Carbon Concentrate	4.52	90.7	245.10
Clean Ash	0.00	197.0	491.91
Process Water	8.03	42.61	139.46

Total Organic Carbon - Fly Ash Water Samples			
Sample	Concentration (ppm)	Sample	Concentration (ppm)
AEP Carbon	9.7	Run #7 Carbon	45.18
AEP Clean Ash	15.8	Run #7 Clean Ash	28.34
DE Carbon	33.62	Run #7 Process Water	3.19
DE Clean Ash	25.47		
DE Process Water	4.15		

Chemical Analysis Pilot Plant Water, Run #7 Ash
D.C. Popko
17 Jan 96

Elemental Analysis of Water (Filtrate) Associated with Each Sample																						
Sample	Si	Al	Ca	Mg	Na	P	K	As	Ag	Ba	Cd	Cr	Pb	Se	Fe	Bi	Ce	Dy	Er	Eu	Ga	Gd
Carbon Concentrate	0.44	0.24	507	bdl	20.9	bdl	1.34	bdl	0.01	1.08	bdl	0.38	bdl	0.23	0.31	0.13	2.63	0.06	0.03	0.06	0.91	0.08
Clean Ash	bdl	0.42	1110	bdl	48.2	bdl	2.16	bdl	0.01	1.66	bdl	0.18	bdl	0.31	0.4	0.13	4.69	0.07	0.03	0.07	1.18	0.1
Process Water	0.16	4.14	42.6	7.44	11.2	bdl	0.56	bdl	0.02	0.07	bdl	bdl	bdl	bdl	0.04	0.2	0.14	0.04	0.03	0.02	0.39	0.06
	Hg	Ho	In	La	Lu	Pr	Sc	Sm	Sr	Tl	Tm	U	Y	Yb	Au	B	Be	Co	Cu	Ge	Hf	Ir
Carbon Concentrate	bdl	0.05	0.59	0.05	0.01	1.66	0.02	0.18	2.75	0.17	0.04	2.78	0.03	0.01	0.04	9.82	bdl	0.02	0.03	0.02	0.03	0.02
Clean Ash	0.01	0.07	0.62	0.07	0.01	3.25	0.02	0.24	4.99	0.14	0.07	4.06	0.04	0.01	0.06	5.92	bdl	0.04	0.08	0.04	0.04	0.02
Process Water	0.01	0.04	0.4	0.04	0.01	0.48	0.02	0.11	0.15	0.25	0.03	0.42	0.02	0.01	0.03	0.27	bdl	0.01	0.01	0.02	0.07	0.02
	Li	Mn	Nb	Ni	Os	Pd	Pt	Re	Rh	Ru	Sb	Sn	Ta	Ti	V	W	Zn	Zr				
Carbon Concentrate	0.04	bdl	0.07	0.02	0.09	0.12	0.06	0.02	0.21	0.05	0.03	0.03	0.29	0.01	0.11	0.35	1.09	0.01				
Clean Ash	0.08	bdl	0.11	0.04	0.15	0.17	0.07	0.01	0.32	0.09	0.06	0.05	0.39	0.01	0.15	0.53	1.95	0.01				
Process Water	0.01	bdl	0.01	0.01	0.08	0.05	0.04	0.02	0.16	0.03	0.07	0.09	0.21	bdl	0.04	0.38	0.29	bdl				
bdl = below detection limit																						

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Fly-ash Waters, Pilot Plant Run #7

D.C. Popko

17 Jan 96

	Total Residue Dried at 103-105°C			Total Filterable Residue Dried at 180°C			Total Filterable Residue Dried at 103-105°C		
	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)
Sample	<u>Dish (mg)</u>	<u>Residue (mg)</u>	<u>(mg/L)</u>	<u>Dish (mg)</u>	<u>Residue (mg)</u>	<u>Residue (mg/L)</u>	<u>Dish (mg)</u>	<u>Residue (mg)</u>	<u>Residue (mg/L)</u>
Carbon									
Concentrate	18,750.90	18,775.30	1,686.67	17,500.50	17,525.20	1,646.67	17,500.50	17,525.60	1,673.33
Clean Ash	20,104.20	20,149.30	3,006.67	16,052.20	16,092.70	2,700.00	16,052.20	16,094.70	2,833.33
Process Water	18,210.60	18,211.50	60.00	18,423.90	18,424.60	46.67	18,424.00	18,424.80	53.33

	Total Non-Filterable Residue			Total Volatile and Fixed Residue at 550°C				
	Weight of Dish (mg)	Weight of Dish + Residue (mg)	Total Filterable Residue (mg/L)	Weight of Dish (mg)	Weight of Dish + Residue (mg) Before Ignition	Weight of Dish + Residue (mg) After Ignition	Volatile Residue (mg/L)	Fixed Residue (mg/L)
Sample	<u>Dish (mg)</u>	<u>Residue (mg)</u>	<u>Residue (mg/L)</u>	<u>Dish (mg)</u>	<u>Before Ignition</u>	<u>After Ignition</u>	<u>(mg/L)</u>	<u>(mg/L)</u>
Carbon								
Concentrate	144	144.2	2	18,750.00	18,775.30	18,772.70	173.33	1,513.33
Clean Ash	146.1	147.1	10	20,104.20	20,149.30	20,146.50	186.67	2,820.00
Process Water	143.4	143.4	0	18,210.60	18,211.50	18,210.80	46.67	13.33

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APHA-AWWA-WPCF

Fly Ash Water, Pilot Plant Run #7

D.C. Popko

17 Jan 96

Sample	Mg (ppm)	Ca (ppm)	Hardness
Carbon Concentrate	0.00	507.00	1,265.98
Clean Ash	0.00	1,110.00	2,771.67
Process Water	7.44	42.60	137.01

Appendix 4

Scanning Electron Microscopy Results

SCANNING ELECTRON MICROSCOPE STUDY OF THE AEP ASH

The scanning electron microscope (SEM) produces secondary electron images (SEIs), which illustrate the morphology of particles as small as nanometers. Backscattered electron images (BEIs) give both morphological information and concentrations of heavy elements such as iron rich particles. It is because in BEIs, heavy elements, e.g., iron, will produce bright regions on the image and light elements, such as aluminum silicates will be dark, and carbon particles will be the darkest. Therefore, BEIs can give immediate qualitative information about the compositional variation of particles. The electron beam can also be positioned stationary on a particle and obtain compositional information of regions as small as microns, using energy dispersive spectroscopy (EDS). Integrated digital image analysis allowed us to analyze each particle individually.

As-received ash and the separation products from beneficiation of as-received ash were examined in the SEM for particle size range, morphology, and composition of individual particles. Each ash and ash products was examined individually. A small sample of fly ash was sprinkled from a spatula onto a strip of double adhesive carbon tape on a carbon plug. The mount was tapped gently on the side to distribute the ash particles. The mount was then carbon coated for conductivity and samples were examined in the SEM for morphological characterization. Backscattered electron images (BEIs) were obtained to show chemical variability of particles; secondary electron images (SEIs) were acquired when high resolution of surface properties was needed.

Chemical characterization of particles was accomplished through the use of energy dispersive spectroscopy (EDS) at 15 to 25 KV accelerating voltage and a current of approximately 0.2 nanoamperes. K radiation was used for all elements. The beam was directed to each particle and the resulting spectrum analyzed for Na, Mg, Al, Si, S, P, K, Ca, Fe, and Ti, calculated as oxides. Elements lighter than Na cannot be quantified by this method, detection limits are approximately 0.5 wt%. Strictly speaking, a quantitative analysis of particles with irregular surfaces is not possible since x-rays will be generated in random directions as a function of surface shape. This will cause errors in corrections made for interferences due to absorption, atomic number, and fluorescence; it will also skew the intensity measurement from the sample used in the quantitation ratio ($I_{\text{sample}}/I_{\text{standard}}$). For that reason, most of the semi-quantitative analysis performed in this study will be discussed rather than inserted into a table, to prevent a casual reader from misinterpreting the precision of the result. However, the analytical totals obtained from analysis of irregular shaped samples will give an approximation of elemental proportions in the particle, and allow us to classify the particles into compositional types.

The following descriptions were based on a combination of the above techniques.

AEP ash: A Class F Fly ash from American Electric Power, Glen Lyn Plant, Unit #6. The NO_x control is staged combustion, and the coal is a low sulfur (<1%) eastern bituminous coal.

As-received AEP ash: As-received AEP ash consisted of both amorphous particles and spheres, with amorphous particles dominating the large particles, and spheres dominating the small particles. Maximum particle size was approximately 140 micrometers.

The amorphous particles in the AEP ash have compositions of approximately 45 to 77 wt% SiO₂,

15 to 23 wt% Al_2O_3 , and 3.0 to 4.5 wt% iron oxide, with remainder as others. The spherical particles in the AEP ash have a average composition of approximately 55 wt% SiO_2 , 33 wt% Al_2O_3 , and 1.5 to 3.0 wt% iron oxide, with remainder as others. The composition for the iron spheres is approximately 69 to 88 wt% iron oxide, 7 to 20 wt% SiO_2 , and 3.0 to 9.0 wt% of Al_2O_3 , with remainder as others.

A photo of a typical as-received fly ash sample is given in Photo 0425.

As-Received Fly Ash

Separation Products from AEP Ash

Cleaned AEP ash: Similarly to as-received AEP ash, cleaned AEP ash also consisted of both amorphous particles and spheres, with spheres dominating. The maximum particle size in cleaned AEP ash was approximately 50 micrometers which is much smaller than that of as-received AEP ash. It is because a screen separation was applied to as-received AEP ash to remove coarser particles.

Photo 0423 shows a typical clean fly ash sample. This appears to be a uniform material with little contamination by carbon or magnetic particles.

Clean Fly Ash

Photo 0416 shows cenospheres from a Class F ash. The product is well cleaned and contains little contamination from carbon or magnetic particles. Al/Si ratios in the spheres varied from 1:1 to 1:2.

Cenospheres

Photo 0428 shows the magnetic fraction from a Class F fly ash. As shown, the magnetic fraction contains spheres with varying shape and amount of magnetite. Polished cross sections of this fraction indicate that the features are structural, not just surface features. Magnetite crystallizes as skeletal crystals (far right center) in glass matrix, multiple crystals in a glass matrix (upper right), particles which are pure magnetite (small angular grain in upper left of center), and everything in between.

Magnetics

Photo 0441 shows a nearly pure carbon particle.

Carbon

Appendix 5

Detailed Laboratory Flotation Test Data

LABORATORY FLOTATION TEST PROGRAM RESULTS

AEP ASH

TEST No.	IMP #	Ash Type	Froth %Wt	Froth %LOI	Froth %LOI Rec	Cell %Wt	Cell %LOI	Cell % LOI Rec	Collector #/T	Frother #/T	Cond. Time (m)	%Solids	pH Modifier	Dosage
232332	54	AEP	61.25	43.14	99.91	38.75	0.06	0.09	11.5	1.67	5	25.0	NA	NA
222331	90	AEP	56.61	45.95	99.80	43.49	0.12	0.20	11.5	1.67	5	18.0	NaOH	5.0
232232	51	AEP	59.89	44.05	99.82	40.11	0.12	0.18	10.0	1.67	5	25.0	NA	NA
232331	108	AEP	40.40	42.73	99.21	40.40	0.23	0.79	11.5	1.67	5	25.0	NaOH	7.0
232132	48	AEP	58.28	44.67	99.58	41.72	0.26	0.42	8.5	1.67	5	25.0	NA	NA
222221	86	AEP	54.16	48.95	99.47	45.84	0.31	0.53	10.0	1.25	5	18.0	NaOH	5.5
222232	33	AEP	54.96	48.22	99.48	45.04	0.31	0.52	10.0	1.67	5	18.0	NA	NA
222322	35	AEP	54.45	48.78	99.35	45.55	0.38	0.65	11.5	1.25	5	18.0	NA	NA
212332	18	AEP	49.58	51.73	99.18	50.42	0.42	0.82	11.5	1.67	5	10.0	NA	NA
222222	32	AEP	48.39	51.22	99.13	51.61	0.42	0.87	10.0	1.25	5	18.0	NA	NA
232231	105	AEP	53.08	41.39	99.03	46.92	0.46	0.97	10.0	1.67	5	25.0	NaOH	7.0
222132	30	AEP	55.71	46.89	99.19	44.29	0.48	0.81	8.5	1.67	5	18.0	NA	NA
222332	36	AEP	56.08	46.91	99.17	43.92	0.50	0.83	11.5	1.67	5	18.0	NA	NA
212231	69	AEP	54.16	46.29	99.06	45.84	0.52	0.94	10.0	1.67	5	10.0	NaOH	2.5 ml
222231	87	AEP	54.87	45.92	99.08	45.13	0.52	0.92	10.0	1.67	5	18.0	NaOH	5.5
212322	17	AEP	47.07	53.90	98.91	52.93	0.53	1.09	11.5	1.25	5	10.0	NA	NA
232322	53	AEP	56.32	45.92	99.06	43.68	0.56	0.94	11.5	1.25	5	25.0	NA	NA
212331	72	AEP	58.59	42.08	98.97	41.41	0.62	1.03	11.5	1.67	5	10.0	NaOH	2.5
221331	81	AEP	57.72	49.35	99.02	42.28	0.67	0.98	11.5	1.67	1	18.0	NaOH	6.5
212131	66	AEP	52.12	48.83	98.70	47.88	0.70	1.30	8.5	1.67	5	10.0	NaOH	2.5
212132	12	AEP	47.44	53.27	98.52	52.56	0.72	1.48	8.5	1.67	5	10.0	NA	NA
222131	84	AEP	50.65	49.15	98.42	49.35	0.81	1.58	8.5	1.67	5	18.0	NaOH	6.0
212232	15	AEP	46.45	52.72	98.07	53.55	0.90	1.93	10.0	1.67	5	10.0	NA	NA
222321	89	AEP	53.22	49.80	98.42	46.78	0.91	1.58	11.5	1.25	5	18.0	NaOH	5.0
211331	63	AEP	58.61	41.46	98.33	41.39	1.00	1.67	11.5	1.67	1	10.0	NaOH	2.5
232321	107	AEP	55.94	46.94	98.30	44.06	1.03	1.70	11.5	1.25	5	25.0	NaOH	7.0
212122	11	AEP	43.60	58.37	97.49	56.40	1.16	2.51	8.5	1.25	5	10.0	NA	NA
212222	14	AEP	44.75	56.60	97.30	55.25	1.27	2.70	10.0	1.25	5	10.0	NA	NA

LABORATORY FLOTATION TEST PROGRAM RESULTS

AEP ASH

TEST No.	IMP #	Ash Type	Froth %Wt	Froth %LOI	Froth %LOI Rec	Cell %Wt	Cell %LOI	Cell % LOI Rec	Collector #/T	Frother #/T	Cond. Time (m)	%Solids	pH Modifier	Dosage
232222	50	AEP	55.02	46.34	97.79	44.98	1.28	2.21	10.0	1.25	5	25.0	NA	NA
212121	65	AEP	50.34	48.67	97.32	49.66	1.36	2.68	8.5	1.25	5	10.0	NaOH	2.5
231332	45	AEP	58.10	44.29	97.71	41.90	1.44	2.29	11.5	1.67	1	25.0	NA	NA
212221	68	AEP	51.09	47.22	97.07	48.91	1.49	2.93	10.0	1.25	5	10.0	NaOH	2.5
221332	27	AEP	57.13	45.23	97.26	42.87	1.70	2.74	11.5	1.67	1	18.0	NA	NA
211231	60	AEP	51.42	49.53	96.70	48.58	1.79	3.30	10.0	1.67	1	10.0	NaOH	3.0
221232	24	AEP	53.93	47.12	96.86	46.07	1.79	3.14	10.0	1.67	1	18.0	NA	NA
232122	47	AEP	53.27	46.01	96.63	46.73	1.83	3.37	8.5	1.25	5	25.0	NA	NA
211332	9	AEP	47.53	52.00	96.18	52.47	1.87	3.82	11.5	1.67	1	10.0	NA	NA
232221	104	AEP	50.63	48.47	96.30	49.37	1.91	3.70	10.0	1.25	5	25.0	NaOH	7.0
211322	8	AEP	45.59	53.78	94.76	54.41	2.49	5.24	11.5	1.25	1	10.0	NA	NA
222312	34	AEP	46.69	52.53	94.79	53.31	2.53	5.21	11.5	0.83	5	18.0	NA	NA
222122	29	AEP	47.94	52.16	93.68	52.06	3.24	6.32	8.5	1.25	5	18.0	NA	NA
221231	78	AEP	52.73	47.49	94.00	47.27	3.38	6.00	10.0	1.67	1	18.0	NaOH	6.5
232131	102	AEP	55.47	45.61	94.20	44.53	3.50	5.80	8.5	1.67	5	25.0	NaOH	7.0
222121	83	AEP	47.70	50.67	92.00	52.30	4.02	8.00	8.5	1.25	5	18.0	NaOH	6.5
211321	62	AEP	52.03	46.09	92.40	47.97	4.11	7.60	11.5	1.25	1	10.0	NaOH	2.5
211232	6	AEP	43.73	55.17	91.17	56.27	4.15	8.83	10.0	1.67	1	10.0	NA	NA
221221	77	AEP	39.05	50.90	88.18	60.95	4.37	11.82	10.0	1.25	1	18.0	NaOH	5.5
212312	16	AEP	39.56	57.41	88.26	60.44	5.00	11.74	11.5	0.83	5	10.0	NA	NA
211131	57	AEP	49.08	47.08	89.61	50.92	5.26	10.39	8.5	1.67	1	10.0	NaOH	3.0
231232	42	AEP	51.90	45.47	89.41	48.10	5.81	10.59	10.0	1.67	1	25.0	NA	NA
231231	96	AEP	54.46	44.26	89.56	45.54	6.17	10.44	10.0	1.67	1	25.0	NaOH	7.0
221322	26	AEP	50.84	47.26	87.85	49.16	6.76	12.15	11.5	1.25	1	18.0	NA	NA
232121	101	AEP	46.43	47.77	84.96	53.57	7.33	15.04	8.5	1.25	5	25.0	NaOH	7.0
231132	39	AEP	50.88	44.75	86.17	49.12	7.44	13.83	8.5	1.67	1	25.0	NA	NA
231322	44	AEP	47.68	46.05	84.91	52.32	7.46	15.09	11.5	1.25	1	25.0	NA	NA
232312	52	AEP	44.15	50.00	83.43	55.85	7.85	16.57	11.5	0.83	5	25.0	NA	NA

LABORATORY FLOTATION TEST PROGRAM RESULTS

AEP ASH

TEST No.	IMP #	Ash Type	Froth %Wt	Froth %LOI	Froth %LOI Rec	Cell %Wt	Cell %LOI	Cell % LOI Rec	Collector #/T	Frother #/T	Cond. Time (m)	%Solids	pH Modifier	Dosage
231321	98	AEP	51.18	44.50	85.40	48.82	7.98	14.60	11.5	1.25	1	25.0	NaOH	7.0
212311	70	AEP	42.06	49.51	80.64	57.94	8.63	19.36	11.5	0.83	5	10.0	NaOH	2.5
232212	49	AEP	40.27	50.87	79.54	59.73	8.82	20.46	10.0	0.83	5	25.0	NA	NA
211132	3	AEP	33.06	57.43	73.87	66.94	10.03	26.13	8.5	1.67	1	10.0	NA	NA
222212	31	AEP	37.74	53.74	74.90	62.26	10.92	25.10	10.0	0.83	5	18.0	NA	NA
231131	93	AEP	48.18	44.62	78.65	51.82	11.26	21.35	8.5	1.67	1	25.0	NaOH	7.0
221222	23	AEP	43.85	46.32	76.21	56.15	11.29	23.79	10.0	1.25	1	18.0	NA	NA
232111	100	AEP	39.03	49.01	72.28	60.97	12.03	27.72	8.5	0.83	5	25.0	NaOH	7.0
222311	88	AEP	33.67	50.99	67.80	66.33	12.29	32.20	11.5	0.83	5	18.0	NaOH	5.0
232311	106	AEP	34.72	50.56	67.31	65.28	13.06	32.69	11.5	0.83	5	25.0	NaOH	7.0
221131	75	AEP	39.64	45.66	69.42	60.36	13.21	30.58	8.5	1.67	1	18.0	NaOH	7.0
221132	21	AEP	43.26	47.23	73.12	56.74	13.24	26.88	8.5	1.67	1	18.0	NA	NA
231221	95	AEP	39.97	46.02	69.80	60.03	13.26	30.20	10.0	1.25	1	25.0	NaOH	7.0
231222	41	AEP	63.40	48.25	85.62	36.60	14.04	14.38	10.0	1.25	1	25.0	NA	NA
231331	99	AEP	43.67	44.05	70.32	56.33	14.41	29.68	11.5	1.67	1	25.0	NaOH	7.0
212112	10	AEP	40.48	45.65	67.83	59.52	14.72	32.17	8.5	0.83	5	10.0	NA	NA
211221	59	AEP	37.82	46.09	65.02	62.18	15.08	34.98	10.0	1.25	1	10.0	NaOH	3.0
211122	2	AEP	28.50	57.29	59.49	71.50	15.55	40.51	8.5	1.25	1	10.0	NA	NA
212111	64	AEP	30.37	48.58	57.18	69.63	15.87	42.82	8.5	0.83	5	10.0	NaOH	2.5
231122	38	AEP	63.62	48.35	83.96	36.38	16.16	16.04	8.5	1.25	1	25.0	NA	NA
212321	71	AEP	28.62	52.22	56.29	71.38	16.26	43.71	11.5	1.25	5	10.0	NaOH	2.5
211311	61	AEP	30.77	46.01	54.96	69.23	16.76	45.04	11.5	0.83	1	10.0	NaOH	2.5
211222	5	AEP	26.32	54.04	53.37	73.68	16.86	46.63	10.0	1.25	1	10.0	NA	NA
211312	7	AEP	23.04	55.04	49.20	76.96	17.01	50.80	11.5	0.83	1	10.0	NA	NA
221312	25	AEP	33.33	46.24	57.34	66.67	17.20	42.66	11.5	0.83	1	18.0	NA	NA
232112	46	AEP	80.15	52.48	91.90	19.85	18.69	8.10	8.5	0.83	5	25.0	NA	NA
212212	13	AEP	19.73	57.34	42.67	80.27	18.94	57.33	10.0	0.83	5	10.0	NA	NA
222112	28	AEP	27.27	50.16	49.80	72.73	18.96	50.20	8.5	0.83	5	18.0	NA	NA
211121	56	AEP	31.26	41.02	49.29	68.74	19.19	50.71	8.5	1.25	1	10.0	NaOH	3.0

LABORATORY FLOTATION TEST PROGRAM RESULTS

AEP ASH

TEST No.	IMP #	Ash Type	Froth %Wt	Froth %LOI	Froth %LOI Rec	Cell %Wt	Cell %LOI	Cell % LOI Rec	Collector #/T	Frother #/T	Cond. Time (m)	%Solids	pH Modifier	Dosage
222211	85	AEP	21.98	50.68	42.59	78.02	19.24	57.41	10.0	0.83	5	18.0	NaOH	6.0
221311	79	AEP	26.93	46.36	46.81	73.07	19.42	53.19	11.5	0.83	1	18.0	NaOH	6.5
231121	92	AEP	28.67	46.05	48.72	71.33	19.48	51.28	8.5	1.25	1	25.0	NaOH	7.0
231312	43	AEP	24.91	45.21	42.67	75.09	20.15	57.33	11.5	0.83	1	25.0	NA	NA
212211	67	AEP	24.92	45.19	42.57	75.08	20.23	57.43	10.0	0.83	5	10.0	NaOH	2.5
211212	4	AEP	17.45	52.92	35.56	82.55	20.27	64.44	10.0	0.83	1	10.0	NA	NA
211211	58	AEP	20.94	47.12	37.85	79.06	20.49	62.15	10.0	0.83	1	10.0	NaOH	3.0
221212	22	AEP	15.10	52.57	31.09	84.90	20.72	68.91	10.0	0.83	1	18.0	NA	NA
232211	103	AEP	19.45	51.78	37.48	80.55	20.86	62.52	10.0	0.83	5	25.0	NaOH	7.0
221122	20	AEP	25.92	47.24	44.11	74.08	20.94	55.89	8.5	1.25	1	18.0	NA	NA
231311	97	AEP	24.78	45.14	41.25	75.22	21.18	58.75	11.5	0.83	1	25.0	NaOH	7.0 ml
221321	80	AEP	23.44	47.59	40.58	76.56	21.33	59.42	11.5	1.25	1	18.0	NaOH	6.5
221121	74	AEP	18.21	49.55	34.00	81.79	21.42	66.00	8.5	1.25	1	18.0	NaOH	6.7
231211	94	AEP	20.79	46.41	36.18	79.21	21.49	63.82	10.0	0.83	1	25.0	NaOH	7.0
211112	1	AEP	14.14	50.35	27.67	85.86	21.68	72.33	8.5	0.83	1	10.0	NA	NA
222111	82	AEP	17.74	51.12	33.52	82.26	21.87	66.48	8.5	0.83	5	18.0	NaOH	6.5
221211	76	AEP	14.65	44.03	25.03	85.35	22.64	74.97	10.0	0.83	1	18.0	NaOH	7.1
221111	73	AEP	17.59	43.93	29.21	82.41	22.72	70.79	8.5	0.83	1	18.0	NaOH	6.0
231111	91	AEP	16.29	45.58	28.07	83.71	22.73	71.93	8.5	0.83	1	25.0	NaOH	7.1
231212	40	AEP	77.65	45.50	87.24	22.35	23.13	12.76	10.0	0.83	1	25.0	NA	NA
221112	19	AEP	15.97	45.88	26.86	84.03	23.75	73.14	8.5	0.83	1	18.0	NA	NA
231112	37	AEP	84.06	46.41	90.78	15.94	24.86	9.22	8.5	0.83	1	25.0	NA	NA
211111	55	AEP	13.51	41.54	20.64	86.49	24.96	79.36	8.5	0.83	1	10.0	NaOH	2.5 ml

LABORATORY FLOTATION TEST PROGRAM RESULTS - NPC Ash														
TEST NUM.	IMP NUM.	ASH TYPE	FROTH			CELL				COLL. #/T	FROTH. #/T	COND. TIME (MIN)	% SOL.	pH
			%WT.	% C	% C REC.	%WT.	% C	% C REC.						
132332	54	NPC	33.50	8.10	79.83	66.50	1.03	20.17		8.26	1.31	5	25.0	natural
132322	53	NPC	31.11	8.33	78.40	68.89	1.04	21.60		8.26	1.09	5	25.0	natural
132312	52	NPC	31.51	8.66	77.07	68.49	1.19	22.93		8.26	0.87	5	25.0	natural
122332	36	NPC	29.79	8.45	74.84	70.21	1.21	25.16		8.26	1.31	5	18.0	natural
122322	35	NPC	28.39	8.73	74.05	71.61	1.21	25.95		8.26	1.09	5	18.0	natural
132212	49	NPC	27.59	8.47	71.96	72.41	1.26	28.04		7.07	0.87	5	25.0	natural
132222	50	NPC	30.36	7.86	72.73	69.64	1.28	27.27		7.07	1.09	5	25.0	natural
122232	33	NPC	25.12	9.10	69.70	74.88	1.33	30.30		7.07	1.31	5	18.0	natural
112332	18	NPC	24.92	8.22	66.70	75.08	1.36	33.30		8.26	1.31	5	10.0	natural
132232	51	NPC	32.64	7.91	73.68	67.36	1.37	26.33		7.07	1.31	5	25.0	natural
122312	34	NPC	25.14	8.92	66.57	74.86	1.50	33.43		8.26	0.87	5	18.0	natural
122222	32	NPC	22.42	10.20	65.77	77.58	1.53	34.23		7.07	1.09	5	18.0	natural
122212	31	NPC	20.97	9.64	61.22	79.03	1.62	38.78		7.07	0.87	5	18.0	natural
122132	30	NPC	25.09	8.01	62.18	74.91	1.63	37.82		5.93	1.31	5	18.0	natural
132132	48	NPC	24.97	9.80	66.00	75.03	1.68	34.00		5.93	1.31	5	25.0	natural
112232	15	NPC	23.09	9.24	62.23	76.91	1.68	37.77		7.07	1.31	5	10.0	natural
132122	47	NPC	27.63	7.84	63.93	72.38	1.69	36.07		5.93	1.09	5	25.0	natural
131232	42	NPC	29.80	6.77	63.06	70.20	1.69	36.94		7.07	1.31	1	25.0	natural
131332	45	NPC	32.51	6.39	64.33	67.49	1.71	35.67		8.26	1.31	1	25.0	natural
112322	17	NPC	23.26	9.03	61.23	76.74	1.73	38.77		8.26	1.09	5	10.0	natural
111332	9	NPC	23.76	7.21	55.81	76.22	1.78	44.19		8.26	1.31	1	10.0	natural
112222	14	NPC	24.75	8.28	59.68	75.25	1.84	40.32		7.07	1.09	5	10.0	natural
131322	44	NPC	28.72	6.62	58.60	71.28	1.88	41.40		8.26	1.09	1	25.0	natural
132112	46	NPC	22.29	9.29	58.36	77.71	1.90	41.64		5.93	0.87	5	25.0	natural
131132	39	NPC	29.31	6.67	58.90	70.69	1.93	41.10		5.93	1.31	1	25.0	natural
122122	29	NPC	20.81	8.40	53.09	79.19	1.95	46.91		5.93	1.09	5	18.0	natural
121332	27	NPC	24.77	7.45	54.91	75.23	2.01	45.09		8.26	1.31	1	18.0	natural
122112	28	NPC	20.29	8.58	52.02	79.71	2.02	47.98		5.93	0.87	5	18.0	natural

LABORATORY FLOTATION TEST PROGRAM RESULTS - NPC Ash														
TEST NUM.	IMP NUM.	ASH TYPE	FROTH			CELL				COLL. #/T	FROTH. #/T	COND. TIME (MIN)	% SOL.	pH
			%WT.	% C	% C REC.	%WT.	% C	% C REC.						
112132	12	NPC	21.14	8.82	53.43	78.86	2.06	46.57		5.93	1.31	5	10.0	natural
131122	38	NPC	29.31	6.52	56.69	70.69	2.07	43.31		5.93	1.09	1	25.0	natural
121232	24	NPC	26.78	6.79	54.47	73.22	2.08	45.53		7.07	1.31	1	18.0	natural
131222	41	NPC	30.87	6.01	56.25	69.13	2.09	43.75		7.07	1.09	1	25.0	natural
112212	13	NPC	22.96	6.94	49.52	77.04	2.11	50.48		7.07	0.87	5	10.0	natural
112122	11	NPC	20.40	8.53	50.73	79.60	2.12	49.27		5.93	1.09	5	10.0	natural
112312	16	NPC	24.92	7.25	53.20	75.08	2.12	46.80		8.26	0.87	5	10.0	natural
131112	37	NPC	22.47	7.14	48.91	77.53	2.16	51.09		5.93	0.87	1	25.0	natural
121322	26	NPC	22.73	7.57	50.37	77.27	2.20	49.63		8.26	1.09	1	18.0	natural
121222	23	NPC	22.36	7.14	48.33	77.64	2.20	51.67		7.07	1.09	1	18.0	natural
131312	43	NPC	25.22	7.65	53.63	74.78	2.23	46.37		8.26	0.87	1	25.0	natural
111322	8	NPC	22.58	7.03	47.72	77.42	2.24	52.28		8.26	1.09	1	10.0	natural
131212	40	NPC	22.70	7.94	50.27	77.30	2.31	49.73		7.07	0.87	1	25.0	natural
121312	25	NPC	19.76	7.88	45.28	80.24	2.35	54.72		8.26	0.87	1	18.0	natural
111232	6	NPC	23.05	6.90	46.00	76.95	2.43	54.00		7.07	1.31	1	10.0	natural
121122	20	NPC	21.42	7.14	44.36	78.58	2.44	55.64		5.93	1.09	1	18.0	natural
111132	3	NPC	20.51	6.87	41.88	79.49	2.46	58.12		5.93	1.31	1	10.0	natural
121132	21	NPC	21.52	6.79	42.80	78.48	2.49	57.20		5.93	1.31	1	18.0	natural
121212	22	NPC	20.24	6.92	40.91	79.76	2.54	59.09		7.07	0.87	1	18.0	natural
112112	10	NPC	25.64	6.29	46.09	74.38	2.54	53.91		5.93	0.87	5	10.0	natural
111122	2	NPC	22.24	6.30	41.30	77.76	2.56	58.70		5.93	1.09	1	10.0	natural
111312	7	NPC	22.32	6.16	40.90	77.68	2.56	59.10		8.26	0.87	1	10.0	natural
121112	19	NPC	17.45	7.09	36.84	82.55	2.57	63.16		5.93	0.87	1	18.0	natural
111112	1	NPC	25.04	5.31	40.85	74.96	2.57	59.15		5.93	0.87	1	10.0	natural
111222	5	NPC	22.58	6.58	42.23	77.42	2.62	57.77		7.07	1.09	1	10.0	natural
111212	4	NPC	24.41	5.74	40.03	75.59	2.78	59.97		7.07	0.87	1	10.0	natural

SUMMARY OF LABORATORY FLOTATION RESULTS															
Test #	Ash Type	Collector		Frother		Clean Ash		Carbon Concentrate			Screen Fraction		Middlings		Remarks
		Type	#/T	Type	#/T	%LO I	%wt rec.	%wt	%LOI	%LOI rec.	%wt	%LOI	%wt	%LOI	
1	NPC	mix	2.0	DF	1.54										
2	NPC	mix	2.0	DF	1.45										
3	AEP	mix	3.0	DF	2.8	0.86	55.8	32.9	61.8	87.5	-	-	11.3	21.5	One cleaner stage
4	BGE	mix	2.0	DF	1.35	5.96	75.6	14.5	13.9	28.1	-	-	9.86	6.72	One cleaner stage
5	AEP	mix	3.0	DF	2.8	12.85	74.0	3.9	74.0	12.5	-	-	22.15	47.4	Five cleaner stages
6	AEP	mix	3.75	DF	3.13	1.37	56.4	30.0	51.7	67.6	-	-	13.6	49.0	One scavenger stage, add frother just prior to flot
7	AEP	mix	3.0	DF	2.99	7.27	63.5	22.9	61.8	58.4	-	-	13.6	40.2	Repeat T3 w/ new collector mix
8	AEP	mix	3.0	DF	2.89	15.63	75.7	24.3	43.1	46.9	-	-	-	-	Repeat T7, shorter conditioning time
9	AEP	mix	3.50	DF	2.89	6.24	62.6	37.4	40.5	79.5	-	-	-	-	Repeat T7, more collector, no cleaners
10	AEP	mix	2.5	DF	2.89	12.18	70.0	30.0	48.3	62.9	-	-	-	-	Repeat T9, less collector, no cleaners
11	FA5	mix	1.75	DF	1.35	0.40	70.5	29.5	18.0	94.9	-	-	-	-	baseline for % solids test, 8.09% solids
12	FA5	mix	1.75	DF	1.35	0.35	69.1	30.9	17.2	95.6	-	-	-	-	Repeat T11, 15.28% solids
13	FA5	mix	1.75	DF	1.35	0.51	73.0	27.0	18.8	93.8	-	-	-	-	Repeat T12, 20% solids
14	FA5	mix	1.75	DF	1.35	0.55	65.4	19.5	23.0	79.0	-	-	15.0	5.5	Repeat T13, 25% solids, collected 2 froths
15	FA5	mix	1.75	DF	1.35	0.62	66.0	17.6	21.2	66.3	-	-	16.4	9.1	Repeat T14, 30% solids
16	FA5	mix	1.75	DF	1.35	0.80	64.0	18.8	17.7	58.1	-	-	17.2	11.0	Repeat T15, 35% solids
17	FA5	mix	1.75	DF	1.35	1.53	71.2	16.1	17.2	49.9	-	-	12.7	13.2	Repeat T16, 40% solids
18	AEP	mix	3.0	DF	3.76	6.69	61.5	38.5	50.6	82.6	-	-	-	-	separate conditioning, adjust pH w/ Na2CO3
19	AEP	mix	3.0	DF	3.76	9.95	63.2	36.8	48.4	74.0	-	-	-	-	Repeat T18, pH to 9
20	AEP	mix	3.0	DF	3.76	8.4	67.0	33.0	53.8	76.0	-	-	-	-	No Na2SiO4, used Na2CO3 H2SO4 for pH
21	AEP	mix	3.5	DF	3.76	6.91	70.5	29.5	62.6	79.1	-	-	-	-	Repeat T20 w/ increased collector
22	BGE	mix	2.0	DF	1.35	14.53	70.3	29.7	3.6	9.4	-	-	-	-	
23	AEP	MAS	8.02	DF/P	1.25/2	4.88	67.2	30.6	62.6	82.0	2.2	42.7	-	-	flot -100m fraction, modify reagent scheme
24	AEP	MAS	9.0	DF/P	1.67/2	1.46	61.4	30.8	69.0	90.7	2.2	49.6	5.7	3.8	repeat T23, w/ cleaner flot, increased collector
25	AEP	MAS	10	DF/P	2.3/2	2.22	63.4	29.7	68.0	88.2	2.5	45.4	4.4	3.4	Repeat T24, increased collector
26	AEP	MAS	10	DF/P	1.67/2	0.35	57.1	28.5	74.1	93.3	2.4	44.5	11.9	5.0	Repeat T25 w/ dif. flot cell, stage add frother
27	AEP	mix	10	DF/P	1.25/2	0.40	54.5	42.3	51.1	92.9	3.2	44.8	-	-	Repeat T26 w/ different collector
28	AEP	MAS	10	DF	1.25	0.18	45.6	51.2	42.6	94.0	3.1	42.4	-	-	DF frother only

SUMMARY OF LABORATORY FLOTATION RESULTS															
Test #	Ash Type	Collector		Frother		Clean Ash		Carbon Concentrate			Screen Fraction		Middlings		Remarks
		Type	#/T	Type	#/T	%LOI	%wt rec.	%wt	%LOI	%LOI rec.	%wt	%LOI	%wt	%LOI	
29	BGE	mix	3.0	P	0.63	2.76	72.6	26.1	15.4	62.1	1.3	34.4	-	-	
30	BGE	mix	3.5	P	0.63	3.89	70.8	28.1	12.7	53.3	1.1	34.2	-	-	Repeat T29 w/ more collector
31	BGE	mix	2.5	P	0.63	3.89	72.6	26.0	15.6	49.8	1.3	36.0	-	-	Repeat T29 w/ less collector
32	BGE	mix	4.0	P	0.84	0.92	71.2	27.6	20.4	84.2	1.2	33.2	-	-	Repeat T30 w/ more collector and frother
33	BGE	mix	4.5	P	1.05	1.15	71.8	13.5	37.6	77.2	0.9	30.4	13.8	2.9	Repeat T32 w/ more reagents and 2 clnr stages
34	BGE	mix	4.5	P	1.05	1.02	70.9	10.2	49.0	77.2	0.9	30.6	18.0	3.1	Repeat T33 w/ 3 clnr stages
35	NPC	mix	1.4	P	0.63	1.36	82.7	3.6	24.8	28.8	3.3	10.4	10.3	7.1	Carbon analyses - <u>not</u> LOI
36	NPC	mix	1.75	P	0.84	0.96	80.1	16.2	9.7	59.2	3.7	8.7	-	-	Repeat T35 w/ more reagents, Carbon analyses - <u>not</u> LOI

SUMMARY OF LABORATORY FLOTATION RESULTS													
Test#	Ash Type	Collector		Frother		Clean Ash		Carbon Concentrate			Middlings		Remarks
		Type	#/T	Type	#/T	%LOI	%wt rec.	%wt	%LOI	%LOI rec.	%wt	%LOI	
M2	B2	mix2		PO		0.46	66.89	22.61	57.23	96.88	10.51	1.04	Flot feed is -100m mat'l, no data is included on +100m
M3	B2	mix2		PO		0.43	64.27	23.76	53.03	96.73	11.97	1.25	Flot feed is -100m mat'l, no data is included on +100m
M4	500	mix2		PO		3.03	51.62	37.91	27.74	81.76	10.47	7.47	Flot feed is -100m mat'l, no data is included on +100m
M5	500	mix2		PO		1.65	47.45	42.54	30.68	92.89	10.01	2.16	Flot feed is -100m mat'l, no data is included on +100m
M8	A2	mix2		PO		0.76	60.53	26.04	57.40	95.08	13.43	2.33	Flot feed is -100m mat'l, no data is included on +100m
M9	A2	mix2		PO		0.60	57.83	28.32	54.12	96.23	13.84	1.83	Flot feed is -100m mat'l, no data is included on +100m
M10	A2	mix2		PO		1.04	66.27	22.70	59.61	93.56	11.03	2.20	Flot feed is -100m mat'l, no data is included on +100m
M11	B2	mix2		PO		1.02	76.54	14.90	61.31	78.23	8.57	20.55	Flot feed is -100m mat'l, no data is included on +100m
M12	900	mix2		PO		1.31	56.51	31.49	63.56	95.46	12.00	1.76	Flot feed is -100m mat'l, no data is included on +100m
M14	900	mix2		PO		17.20	81.27	9.18	63.37	26.17	9.55	25.41	Flot feed is -100m mat'l, no data is included on +100m

SUMMARY OF LABORATORY FLOTATION RESULTS													
Test#	Ash Type	Collector		Frother		Clean Ash		Carbon Concentrate			Middlings		Remarks
		Type	#/T	Type	#/T	%LOI	%wt rec.	%wt	%LOI	%LOI rec.	%wt	%LOI	
M15	900	mix2		PO		0.84	48.90	36.56	58.10	96.78	14.55	2.04	Flot feed is -100m mat'l, no data is included on +100m
M16	500	mix2		PO		14.53	70.05	18.16	13.14	18.20	11.80	4.63	Flot feed is -100m mat'l, no data is included on +100m
M17	B2	mix2		PO		0.35	69.40	19.40	61.43	96.84	11.19	1.30	Flot feed is -100m mat'l, no data is included on +100m
M18	A2	mix2		PO		1.11	63.15	22.47	65.47	96.76	14.38	1.93	Flot feed is -100m mat'l, no data is included on +100m
M19	900	mix2		PO		1.02	48.36	32.71	67.41	96.61	18.93	1.13	Flot feed is -100m mat'l, no data is included on +100m
M20	500	mix2		PO		0.74	42.91	40.59	38.62	96.81	16.50	1.21	Flot feed is -100m mat'l, no data is included on +100m
Tests # M1, M6, M7, and M13 did not produce results or were not conducted.													

Appendix 6

Dewatering Test Results

Institute of Materials Processing

Settling Tests

Material : AEP Clean Ash

Solid Content 5 %

Total Volume 285

Date 10/18/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Line (ml)	Comments
0.0	285.0		15.0		
0.5	280.0		20.0		
1.0	280.0		25.0		
1.5	275.0		30.0		Clearing On Top
2.0	275.0		40.0		
2.5	275.0		50.0		
3.0	275.0		60.0		
3.5	275.0		120.0		Clear At 245
4.0	275.0		180.0		Clear At 245
4.5	275.0		360.0		Clear At 245
5.0	270.0		1440.0		All Clear
10.0		Cloudy

Institute of Materials Processing

Settling Tests

Material : NPC Clean Ash

Solid Content 5 %

Total Volume 285

Date 10/18/95

Time (min)	Line (ml)	Comments	Time (min)	Line (ml)	Comments
0.0	0.0		15.0	25.0	
0.5	0.0		20.0	25.0	
1.0	0.0		25.0	25.0	
1.5	0.0		30.0	25.0	
2.0	30.0		40.0	25.0	Clear At 270
2.5	25.0		50.0	25.0	
3.0	25.0		60.0	25.0	Clear At 265
3.5	25.0		120.0	24.0	Clear At 250
4.0	25.0		180.0	24.0	
4.5	25.0		360.0	24.0	
5.0	25.0		1440.0	24.0	All Clear
10.0	25.0	Clear At 275

Institute of Materials Processing

Settling Tests

Material : AEP Clean Ash

Solid Content 10 %

Total Volume 285

Date 10/12/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	280.0		15.0	255.0	Cloudy
0.5	270.0		20.0	26.0	
1.0	270.0		25.0	26.0	
1.5	270.0		30.0	26.0	
2.0	265.0		40.0	26.0	
2.5	265.0		50.0	26.0	
3.0	265.0	Clearing At Top	60.0	26.0	
3.5	265.0		120.0	26.0	
4.0	265.0		180.0	26.0	
4.5	265.0		360.0	26.0	Clearing
5.0	265.0		1440.0	26.0	Clearing
10.0	260.0

Institute of Materials Processing

Settling Tests

Material : NPC Clean Ash

Solid Content 10 %

Total Volume 280

Date 10/12/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	280.0		15.0	40.0	
0.5	260.0		20.0	40.0	Clearing
1.0	225.0		25.0	40.0	
1.5	175.0		30.0	40.0	
2.0	160.0		40.0	40.0	
2.5	130.0		50.0	40.0	
3.0	100.0		60.0	40.0	
3.5	60.0		120.0	40.0	Almost Clear
4.0	50.0	Clearing At Top	180.0	40.0	
4.5	50.0		360.0	40.0	
5.0	45.0		1440.0	40.0	Clear
10.0	40.0	Cloudy

Institute of Materials Processing

Settling Tests

Material : AEP Clean Ash

Solid Content 15 %

Total Volume 267

Date 10/16/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	267.0		15.0	48.0	
0.5	265.0		20.0	46.0	Clearing
1.0	265.0		25.0	45.0	
1.5	260.0		30.0	44.0	
2.0	260.0		40.0	43.0	
2.5	260.0		50.0	43.0	
3.0	260.0		60.0	43.0	
3.5	260.0		120.0	43.0	Almost Clear
4.0	260.0	Clearing At Top	180.0	43.0	
4.5	260.0		360.0	43.0	
5.0	260.0		1440.0	43.0	Clear
10.0	255.0	Cloudy

Institute of Materials Processing

Settling Tests

Material : NPC Clean Ash

Solid Content 15 %

Total Volume 270

Date 10/16/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	270.0		15.0	63.0	
0.5	240.0		20.0	61.0	
1.0	225.0		25.0	60.0	
1.5	210.0		30.0	60.0	
2.0	170.0		40.0	60.0	
2.5	160.0		50.0	60.0	
3.0	145.0		60.0	60.0	
3.5	130.0		120.0	60.0	Clear At 250 ml
4.0	105.0		180.0	60.0	
4.5	95.0		360.0	60.0	Clear At 240 ml
5.0	90.0	Clearing At Top	1440.0	60.0	All Clear
10.0	68.0

Institute of Materials Processing

Settling Tests

Material : AEP Clean Ash

Solid Content 20 %

Total Volume 262

Date 10/18/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	262.0		15.0	75.0	All Cloudy
0.5	260.0		20.0	64.0	
1.0	258.0		25.0	62.0	
1.5	255.0		30.0	60.0	
2.0	255.0		40.0	58.0	
2.5	255.0		50.0	57.0	Clearing On Top
3.0	254.0		60.0	57.0	
3.5	252.0		120.0	57.0	Clear At 255 ml
4.0	252.0		180.0	57.0	
4.5	251.0		360.0	57.0	
5.0	250.0		1440.0	57.0	All Clear
10.0	140.0

Institute of Materials Processing

Settling Tests

Material : NPC Clean Ash

Solid Content 20 %

Total Volume 262

Date 10/18/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	262.0		15.0	85.0	
0.5	250.0		20.0	81.0	
1.0	238.0		25.0	79.0	
1.5	220.0		30.0	78.0	Clearing On Top
2.0	208.0		40.0	78.0	
2.5	195.0		50.0	78.0	
3.0	188.0		60.0	78.0	
3.5	175.0		120.0	78.0	Clear At 245
4.0	160.0		180.0	78.0	Clear At 240
4.5	152.0		360.0	78.0	Clear At 225
5.0	142.0		1440.0	78.0	All Clear
10.0	96.0	Cloudy

Institute of Materials Processing

Settling Tests

Material : AEP Clean Ash

Solid Content 25 %

Total Volume 255

Date 10/19/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	255.0		15.0	110.0	All Cloudy
0.5	250.0		20.0	86.0	
1.0	245.0		25.0	80.0	
1.5	240.0		30.0	76.0	
2.0	235.0		40.0	73.0	
2.5	230.0		50.0	71.0	Clearing On Top
3.0	225.0		60.0	70.0	
3.5	220.0		120.0	70.0	Clear At 255 ml
4.0	215.0		180.0	70.0	
4.5	210.0		360.0	70.0	
5.0	205.0		1440.0	70.0	All Clear
10.0	155.0

Institute of Materials Processing

Settling Tests

Material : NPC Clean Ash

Solid Content 25 %

Total Volume 255

Date 10/19/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	255.0		15.0	104.0	
0.5	240.0		20.0	100.0	
1.0	230.0		25.0	95.0	Clearing At Top
1.5	220.0		30.0	94.0	
2.0	210.0		40.0	92.0	
2.5	200.0		50.0	91.0	
3.0	193.0		60.0	91.0	
3.5	185.0		120.0	91.0	Clear At 235 ml
4.0	176.0		180.0	91.0	
4.5	170.0		360.0	91.0	Clear At 220 ml
5.0	160.0		1440.0	91.0	All Clear
10.0	118.0

Institute of Materials Processing

Settling Tests

Material : AEP Clean Ash

Solid Content 35 %

Total Volume 245

Date 10/25/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	245.0		15.0	148.0	
0.5	245.0		20.0	120.0	All Cloudy
1.0	240.0		25.0	105.0	
1.5	235.0		30.0	97.0	
2.0	230.0		40.0	88.0	
2.5	227.0		50.0	85.0	
3.0	224.0		60.0	85.0	Clearing At Top
3.5	221.0		120.0	84.0	
4.0	219.0		180.0	84.0	
4.5	215.0		360.0	84.0	
5.0	213.0		1440.0	84.0	Almost Clear
10.0	180.0

Institute of Materials Processing

Settling Tests

Material : NPC Clean Ash

Solid Content 30 %

Total Volume 244

Date 10/25/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	244.0		15.0	130.0	All Cloudy
0.5	240.0		20.0	125.0	
1.0	232.0		25.0	119.0	
1.5	229.0		30.0	115.0	
2.0	224.0		40.0	111.0	
2.5	220.0		50.0	110.0	
3.0	216.0		60.0	110.0	Clear At Top
3.5	213.0		120.0	110.0	
4.0	208.0		180.0	110.0	Clear At 240
4.5	205.0		360.0	110.0	Clear At 210
5.0	201.0		1440.0	110.0	Almost Clear
10.0	165.0

Institute of Materials Processing

Settling Tests

Material : AEP Carbon

Solid Content 5 %

Total Volume 280

Date 10/26/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	280.0		15.0	52.0	
0.5	280.0		20.0	52.0	All Cloudy
1.0	280.0		25.0	52.0	
1.5	280.0		30.0	52.0	
2.0	280.0		40.0	52.0	
2.5	280.0		50.0	51.0	
3.0	280.0		60.0	51.0	Clearing At Top
3.5	280.0		120.0	51.0	
4.0	280.0		180.0	51.0	
4.5	280.0		360.0	51.0	Cloudy
5.0	280.0		1440.0	48.0	Clear
10.0	280.0

Institute of Materials Processing

Settling Tests

Material : NPC Carbon

Solid Content 5 %

Total Volume 280

Date 10/26/95

Time (min)	Line (ml)	Comments	Time (min)	Line (ml)	Comments
0.0	280.0		15.0	65.0	All Cloudy
0.5	280.0		20.0	60.0	
1.0	280.0		25.0	58.0	
1.5	280.0		30.0	56.0	
2.0	280.0		40.0	55.0	Clearing, Few Suspended Particles
2.5	280.0		50.0	54.0	
3.0	280.0		60.0	53.0	
3.5	280.0		120.0	52.0	
4.0	280.0		180.0	52.0	
4.5	280.0		360.0	51.0	Almost Clear
5.0	280.0		1440.0	51.0	Clear
10.0	80.0

Institute of Materials Processing

Settling Tests

Material : AEP Carbon

Solid Content 10 %

Total Volume 285

Date 11/20/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	285.0		15.0	285.0	
0.5	285.0		20.0	100.0	All Cloudy
1.0	285.0		25.0	98.0	Party Cloudy
1.5	285.0		30.0	96.0	
2.0	285.0		40.0	92.0	
2.5	285.0		50.0	90.0	
3.0	285.0		60.0	90.0	
3.5	285.0		120.0	90.0	
4.0	285.0		180.0	90.0	
4.5	285.0		360.0	90.0	Almost Clear
5.0	285.0		1440.0	90.0	Clear
10.0	285.0

Institute of Materials Processing

Settling Tests

Material : NPC Carbon

Solid Content 10 %

Total Volume 278

Date 11/20/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	278.0		15.0	200.0	Party Cloudy
0.5	278.0		20.0	175.0	
1.0	278.0		25.0	150.0	
1.5	278.0		30.0	135.0	
2.0	278.0		40.0	120.0	
2.5	278.0		50.0	100.0	
3.0	278.0		60.0	90.0	
3.5	278.0		120.0	88.0	
4.0	278.0		180.0	86.0	
4.5	278.0		360.0	86.0	Almost Clear
5.0	278.0		1440.0	85.0	Clear
10.0	210.0

Institute of Materials Processing

Settling Tests

Material : AEP Carbon

Solid Content 15 %

Total Volume 258

Date 11/21/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	258.0		15.0	258.0	
0.5	258.0		20.0	258.0	
1.0	258.0		25.0	152.0	Party Cloudy
1.5	258.0		30.0	140.0	
2.0	258.0		40.0	132.0	
2.5	258.0		50.0	132.0	
3.0	258.0		60.0	132.0	
3.5	258.0		120.0	130.0	
4.0	258.0		180.0	130.0	
4.5	258.0		360.0	130.0	
5.0	258.0		1440.0	130.0	Air Bubbles At Bottom Of Cylinder
10.0	258.0

Institute of Materials Processin

Settling Tests

Material : NPC Carbon

Solid Content 15 %

Total Volume 260

Date 11/21/95

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	260.0		15.0	250.0	Clearing
0.5	260.0		20.0	235.0	
1.0	260.0		25.0	225.0	Partly Cloudy
1.5	260.0		30.0	217.0	
2.0	260.0		40.0	200.0	
2.5	260.0		50.0	163.0	
3.0	260.0		60.0	161.0	
3.5	260.0		120.0	125.0	
4.0	260.0		180.0	125.0	
4.5	260.0		360.0	122.0	
5.0	260.0		1440.0	120.0	
10.0	260.0

Institute of Materials Processin

Settling Tests

Material : AEP Carbon

Solid Content 30 %

Total Volume 285

Date 11/28/95

Flocculant Superfloc 210 (1ml of 0.125% sol.)

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	285.0		15.0	121.0	
0.5	265.0		20.0	112.0	
1.0	250.0		25.0	110.0	
1.5	238.0		30.0	108.0	
2.0	225.0		40.0	107.0	
2.5	210.0		50.0	107.0	
3.0	198.0		60.0	106.0	
3.5	188.0		120.0	106.0	All Clear
4.0	178.0		180.0	106.0	
4.5	170.0		360.0	106.0	
5.0	165.0		1440.0	106.0	
10.0	133.0

Institute of Materials Processing

Settling Tests

Material : NPC Carbon

Solid Content 30 %

Total Volume 315

Date 11/28/95

Flocculant Superfloc 210 (1ml of 0.125% sol.)

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	315.0		15.0	130.0	
0.5	285.0		20.0	127.0	
1.0	262.0		25.0	125.0	
1.5	232.0		30.0	124.0	
2.0	215.0		40.0	123.0	
2.5	200.0		50.0	123.0	
3.0	188.0		60.0	122.0	All Clear
3.5	178.0		120.0	121.0	
4.0	170.0		180.0	121.0	
4.5	165.0		360.0	121.0	
5.0	160.0		1440.0	121.0	
10.0	138.0

Institute of Materials Processing

Settling Tests

Material : AEP Carbon

Solid Content !% %

Total Volume 315

Date 11/28/95

Flocculant Superfloc 210 (1ml of 0.125% sol.)

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	315.0		15.0	215.0	
0.5	310.0		20.0	193.0	
1.0	300.0		25.0	180.0	
1.5	295.0		30.0	175.0	
2.0	290.0		40.0	170.0	
2.5	285.0		50.0	169.0	
3.0	282.0		60.0	168.0	
3.5	280.0		120.0	166.0	
4.0	277.0		180.0	166.0	
4.5	275.0		360.0	166.0	
5.0	272.0		1440.0	166.0	
10.0	248.0

Institute of Materials Processing

Settling Tests

Material : NPC Carbon

Solid Content 15 %

Total Volume 340

Date 11/28/95

Flocculant Superfloc 210 (1ml of 0.125% sol.)

Time (min)	Mud Line (ml)	Comments	Time (min)	Mud Line (ml)	Comments
0.0	340.0		15.0	212.0	
0.5	340.0		20.0	200.0	
1.0	340.0		25.0	190.0	
1.5	340.0		30.0	185.0	
2.0	312.0		40.0	174.0	
2.5	305.0		50.0	166.0	
3.0	300.0		60.0	162.0	
3.5	295.0		120.0	150.0	
4.0	289.0		180.0	150.0	
4.5	285.0		360.0	150.0	
5.0	275.0		1440.0	150.0	
10.0	210.0

Appendix 7

Pilot Plant Flowsheets

Appendix 8

Fly Ash Properties for Concrete Applications

Summary of AEP (Class F) Fly Ash Properties			
Chemical Composition	As-received ash	Clean ash	ASTM C 618 (Class F ash)
SiO ₂ (wt%)	44.0	58.6	
Al ₂ O ₃ (wt%)	22.4	29.2	
Fe ₂ O ₃ (wt%)	5.3	5.2	
<i>Total SiO₂+Al₂O₃+Fe₂O₃, (wt%)</i>	<i>71.7</i>	<i>93.0</i>	<i>70 (minimum)</i>
CaO (wt%)	0.76	0.85	
MgO (wt%)	0.86	1.11	
Na ₂ O (wt%)	0.32	0.42	
K ₂ O (wt%)	2.35	3.16	
TiO ₂ (wt%)	1.11	1.33	
P ₂ O ₅ (wt%)	0.03	0.09	
LOI (wt%)	21.7	0.40	6.0 (maximum)
SO ₃ (wt%)	NA	NA	5.0 (maximum)
Total (wt%)	98.8	100.4	
Physical Test Results			
Moisture content (%)	0.25	0.20	3.0 (maximum)
325 mesh retained (%)	32.9	23.1	34 (maximum)
Specific gravity (g/cm ³)	2.13	2.19	
<i>N.A. = not available</i>			

Summary of BGE (Class F) Fly Ash Properties			
Chemical Composition	As-received ash	Clean ash	ASTM C 618 (Class F ash)
SiO ₂ (wt%)	56.6	NA	
Al ₂ O ₃ (wt%)	27.8	NA	
Fe ₂ O ₃ (wt%)	3.3	NA	
Total SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ , (wt%)	87.7	NA	70 (minimum)
CaO (wt%)	1.04	NA	
MgO (wt%)	0.80	NA	
Na ₂ O (wt%)	0.28	NA	
K ₂ O (wt%)	2.25	NA	
TiO ₂ (wt%)	1.50	NA	
P ₂ O ₅ (wt%)	0.01	NA	
LOI (wt%)	6.22	NA	6.0 (maximum)
SO ₃ (wt%)	NA	NA	5.0 (maximum)
Total (wt%)	99.8	NA	
Physical Test Results			
Moisture content (%)	0.17	0.20	3.0 (maximum)
325 mesh retained (%)	19.5	NA	34 (maximum)
Specific gravity (g/cm ³)	2.24	2.20	
N.A. = not available			

Summary of Dust Collector Fly Ash (UPPCO) Properties			
Chemical Compositions (wt%)	As-received ash	Cleaned ash	ASTM C 618 Class F ash
SiO ₂	44.00	57.00	
Al ₂ O ₃	18.80	26.10	
Fe ₂ O ₃	6.25	4.37	
<i>Total SiO₂+Al₂O₃+Fe₂O₃</i>	<i>69.05</i>	<i>87.47</i>	<i>70 (minimum)</i>
CaO	0.76	1.05	
MgO	0.44	0.67	
Na ₂ O	0.22	0.43	
K ₂ O	1.40	1.40	
TiO ₂	0.77	1.14	
P ₂ O ₅	0.28	0.42	
BaO	0.13	0.16	
MnO	0.05	0.05	
LOI (wt%)	29.82	2.53	6.0 (maximum)
SO ₃ (wt%)	0.46	0.10	5.0 (maximum)
Total (wt%)	103.38	95.00	
Physical Test Results			
Moisture content (%)	0.55	0.35	3.0 (maximum)
325 mesh retained (%)	61.50	22.47	34 (maximum)
Specific gravity (g/cm ³)	2.24	2.30	

Summary of FA5 (Class F) Fly Ash Properties			
Chemical Composition	As-received ash	Clean ash	ASTM C 618 (Class F ash)
SiO ₂ (wt%)	54.8	57.5	
Al ₂ O ₃ (wt%)	28.8	30.2	
Fe ₂ O ₃ (wt%)	2.5	3.2	
Total SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ , (wt%)	87.1	90.9	70 (minimum)
CaO (wt%)	0.74	0.77	
MgO (wt%)	0.83	0.87	
Na ₂ O (wt%)	0.29	0.30	
K ₂ O (wt%)	2.70	2.80	
P ₂ O ₅ (wt%)	0.16	0.17	
LOI (wt%)	7.25	0.61	6.0 (maximum)
SO ₃ (wt%)	0.31	0.32	5.0 (maximum)
Total (wt%)	99.11	96.42	
Physical Test Results			
Moisture content (%)	0.28	0.13	3.0 (maximum)
325 mesh retained (%)	9.01	4.91	34 (maximum)
Specific gravity (g/cm ³)	2.22	2.22	

Summary of NPC (Class C) Ash Properties			
Chemical Composition	As-received ash	Clean ash	ASTM C 618 (Class F ash)
SiO ₂ (wt%)	56.9	59.2	
Al ₂ O ₃ (wt%)	16.3	16.0	
Fe ₂ O ₃ (wt%)	4.3	3.7	
Total SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ , (wt%)	77.5	78.92	70 (minimum)
CaO (wt%)	11.18	8.94	
MgO (wt%)	2.04	2.03	
Na ₂ O (wt%)	2.84	3.31	
K ₂ O (wt%)	0.72	0.54	
P ₂ O ₅ (wt%)	0.17	0.06	
Ti ₂ O ₂ (wt%)	0.90	0.76	
Carbon (wt%)	4.0	1.2	
SO ₃ (wt%)	-	0.32	5.0 (maximum)
Total (wt%)	99.35	95.98	
Physical Test Results			
Moisture content (%)			
325 mesh retained (%)			
Specific gravity (g/cm ³)			

Appendix 9

Fracture Surfaces of Polymers

Fracture Surface of Polypropylene with 40 phr Fine Clean AEP Ash

Fracture Surface of Polypropylene with 40 phr CaCO₃

Fracture Surface of Low Density Polyethylene with 40 phr Fine Clean AEP Ash

Fracture Surface of High Density Polyethylene with 40 phr Fine Clean AEP Ash

Fracture Surface of High Density Polyethylene with 40 phr CaCO₃

Appendix 10

Refractory Material from Beneficiated Fly Ash

Refractory Material from Beneficiated Fly Ash

Introduction

Fly ash has a chemical composition and consistency similar to clay. Both materials are aluminosilicate compounds and are powdery when dry. Because of these features fly ash has the potential replacing part of the clay in many clay products. The use of fly ash in ceramic products, such as bricks and ceramic tile has been tried for years. [1] Previous work focused on the use of as-received fly ash in low value applications. Although beneficiation of fly ash adds processing costs to the use of ash, cleaning may make it more suitable for use in the manufacture of more advanced materials such as mullite, an advanced ceramic capable of being synthesized from silicates and alumina.

Mullite is an alumina and silica compound ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) with the following properties:

- chemical and thermal stability
- high refractoriness
- low creep rate
- low thermal expansion and conductivity
- medium strength and toughness
- dielectric properties similar to that of alumina

Because of these properties, mullite is used as 1) a refractory material for lining high temperature furnaces, 2) a matrix material for ceramic composites, 3) a material for turbine engine parts; 4) protective coatings, 5) electronic substrates, and 6) infrared transmitting windows.

Mullite rarely occurs in nature and is generally produced by fusion of alumina and silica in an electric arc furnace. Other ways of producing produce mullite materials include reaction sintering using various aluminum and silicon oxide raw materials or organo-metallic precursors, chemical vapor deposition, and sol-gel techniques.

Currently, mullite sands sell for \$1,500 - \$1900 per ton depending on particle size and the synthesis route. The materials for synthesis include alumina, silica and clay which are priced at about \$1,000, \$20 and \$60 per ton respectively. Beneficiated fly ash is estimated to cost less than \$20 per ton. Since it contains 30% alumina, a 1 to 1 ratio of fly ash to alumina is required to synthesize mullite compared to a 2 to 1 alumina ratio if silica is used. Obviously the lesser requirement for alumina with fly ash synthesized mullite translates into a considerable cost savings.

Experimental

Reaction sintering to synthesize mullite materials was chosen for the work of the present project because of its simplicity. Mullite is a single crystal phase composed of 72% by weight alumina and 28% by weight silica. [2] The composition of the cleaned ash used in the test was about 12 to 27% by weight alumina and 31 to 63% by weight silica. [3] Pure alumina powder was

added to the cleaned ash to make up the alumina deficiency. Under the appropriate sintering conditions, the cleaned ash and alumina powder mixture react to form a single mullite phase material.

In the mullite synthesis test work, both Class C and F fly ashes were used. The effects of different mixture ratios of these cleaned ashes and alumina powder on mullite formation were investigated. For comparison, as-received Class F fly ash was also used to synthesize mullite samples.

The Class F ash used for this study was obtained from Consumers Power in Michigan and the Class C ash from Detroit Edison Belle River Plant, designated as FA5 and FA3 respectively.

Sample Preparation

Three fly ash/alumina ratios were used in the experiments. They are listed in Table A10-1 and labeled, according to the fly ash source, cleaned or as-received ash, and the ash to alumina ratio. Thus FA5-C82 means fly ash from source 5 (Consumers Power in Michigan), cleaned, with an 82:100 ash to alumina mixture ratio. FA5-A91 means fly ash 5, as-received, with a mixture ratio of 91:100. FA5-C115 is cleaned fly ash 5 with a 115:100 mixture ratio.

Table A10-1 Mixture Ratios of Fly Ash and Alumina Powder			
Sample	FA5-C82	FA5-A91	FA5-C115
ash to alumina by weight	82:100	91:100	115:100

Initially, the mixture ratios of Sample FA5-C82 and FA5-A91 were designed to produce a 100 % mullite phase, but the x-ray diffraction analyses revealed the existence of excess alumina. The mixture ratio for mullite FA5-C115 was calculated based on the x-ray results of the quantitative phase analysis of mullite FA5-C82. This mixture ratio was designed to produce exactly 100 % mullite.

Reaction Sintering

The initial sintering experiment was designed to determine the appropriate sintering conditions for mullite formation from fly ash and alumina powder, as well as, for the synthesis of other highly dense materials. Nine 12.7mm diameter by 12.7mm long mullite FA5-C82 samples were sintered at various temperatures and holding times, as listed in Table A10-2. The remaining samples were sintered at 1600°C and held for 2 hours at this temperature.

Table A10-2 Reaction Sintering Parameters			
Sample Number	Heating Rate (hours)	Sintering Temp. (°C)	Holding Time (hours)
FA5-C82-1	3	1400	1
FA5-C82-2	3	1400	2
FA5-C82-3	3	1400	5
FA5-C82-4	3	1500	1
FA5-C82-5	3	1500	2
FA5-C82-6	3	1500	5
FA5-C82-7	3	1600	1
FA5-C82-8	3	1600	2
FA5-C82-9	3	1600	5

Results and Discussions

Effect of Sintering Temperature and Time on Mullite Formation and Density

The nine samples sintered at various temperatures and times described previously were examined by x-ray diffraction analysis to evaluate the mullite formation. Figure A10-1 shows the spectrum of sample FA5-C82-8 diffraction patterns. The spectrums of the other samples looked the same except for different ratios of mullite and corundum phases. The results indicate fly ash and alumina powder are converted to mullite and corundum under all of the sintering conditions evaluated.

Figure A10-1 X-ray Diffraction Pattern Analysis on Sample FA5-C82-8

Figure A10-2 shows there is a slight increase in the ratio of mullite to corundum in the sintered product with increased sintering temperature. Figure A10-3 presents the density results of the nine samples vs. sintering time. The density of the sample series sintered at 1400°C changes only slightly as sintering time increases from one to five hours. The 1500°C sintered samples show an increase in density with increasing sintering time. The density of 1600°C sintered samples increased between the one and two hour sintering times and then remained constant. Higher sintering temperatures produced higher density samples. From the density data and x-ray diffraction analysis results, a 1600°C sintering temperature and 2 hour holding time were chosen as the appropriate sintering condition for the synthesis of mullite from fly ash and alumina powder.

Figure A10-2 Mullite/corundum Ratio vs Sintering Temperature

Figure A10-3 Density of Mullite Sintered at Various Conditions

Comparisons of Fly Ash Synthesized and Commercial Mullites

Mullite samples for mechanical and physical property determinations were sintered for 2 hours at 1600°C. Table A10-3 summarizes the properties of the mullites derived from cleaned and as-received fly ash commercial mullite properties are listed for comparison. Although the color is slightly different, cleaned ash derived mullite has water absorption, density, refractoriness, thermal expansion coefficient, and fracture toughness properties similar to commercial mullite.

Table A10-3 Mullite Properties by Grade

Mullite Products	Water Absorp Ratio %	Density g/cm ³	PCE Cone #	Vicker's Hardness kg/mm ²	Thermal Expansion Coeff. 10 ⁻⁶ /°C	Fracture Toughness MPa m ^{1/2}	Compressive Strength MPa	Color	Sintering Shrink %
Mullite FA-C82	None	2.89	38	780	5.27	2.31*	-	Light Gray	15.4
Mullite FA5-C115	None	2.71	36	643	5.23	1.89*	972	Light Gray	11.2
Mullite FA5-A91	0.21	2.80	38	722	9.28	2.51*	988	Light Gray	11.7
Commercial**	None	2.82	38	-	4.5-5.3	2	-	Buff	N/A

* Measured by the hardness method ⁽²⁾ with an assumption of modules of 225 GPa

** Water absorption, density data from Coors Ceramic Co, others from Engineered Mat'ls Handbook, Vol. 4, Ceramics and Glasses, ASM Internat'l, 1991.

Mullite FA5-A91, derived from as-received fly ash, is similar to commercial mullite in most properties, but the thermal expansion coefficient is 75% higher than the upper limit. This is a serious problem for fly ash derived mullite because low thermal expansion is one of the most important properties required for refractory applications. Materials with low thermal expansion can better stand thermal shock and have better thermal fatigue resistance. Figures A10-4 and A10-5 present typical thermal expansion coefficient curves for cleaned fly ash derived mullite and as-received fly ash derived mullite. In the two Exhibits, the cleaned ash has a smooth length versus temperature curve as temperature increases, but the as-received ash curve shows a sudden length increase at about 570°C. The overall expansion coefficient from room temperature to 1000°C for mullite derived from as-received ash is much higher than that for mullite derived from cleaned ash. Degradation of the thermal expansion property is believed to be caused by impurities in the as-received fly ash. It is concluded that beneficiation is required to prepare fly ash that is suitable for manufacturing such advanced materials.

Figure A10-4 Typical Thermal Expansion Coefficient Curve of As-received Mullite

Figure A10-5 Typical Thermal Expansion Coefficient Curve for Cleaned Fly Ash Derived Mullite

Compared to theoretical results, Mullite FA5-C115 has inferior relative density, refractoriness, hardness, fracture toughness, and sintering shrinkage, but has a comparable thermal expansion coefficient. Mullite material is difficult to consolidate because of its atomic structure.

The lower relative density (measured/theoretical) of Mullite FA5-C115 compared to other mullites was expected because of its 100% mullite phase. The lower mechanical properties for this mullite are possibly caused by greater sample porosity. From an application point of view, some alumina phase excess is desirable because it can increase the density and reduce the possible glassy phase on the grain boundaries.

Mullite was also synthesized from the Class C fly ash and alumina powder using the same procedures discussed above. The melting point of this mullite was found to be below 1350°C. Evidently the Class C fly ash is not suitable for the production of refractory materials because of its high CaO content. The beneficiation process developed in this research did not reduce the CaO content significantly and, therefore, no further ceramic products technology development tests were conducted on the Class C fly ash.

Impurity Level

Specifications in ASTM C467 limit the maximum allowable level of mullite impurities as metal oxides other than aluminum and silicon to 5%. Compositions of the three fly ash derived mullites were analyzed and the results are given in Table A10-4. The numbers in the parentheses are values normalized to 100 %. Normalized impurity levels for the cleaned ash derived Mullite FA5-C82 and Mullite FA5-C115 are below the 5% ASTM standard, but the impurity level of as-received ash derived Mullite FA5-A91 is not.

Table A10-4 Chemical Composition of Fly Ash Derived Mullite			
Component %	Mullite FA5-C82	Mullite FA5-A91	Mullite FA5-C115
SiO ₂	26.96 (31.61)	29.09 (32.25)	32.52 (33.05)
Al ₂ O ₃	54.42 (63.80)	56.31 (62.43)	61.22 (62.23)
Impurities			
FeO	1.54 (1.80)	1.93 (2.14)	1.80 (1.83)
MgO	0.43 (0.50)	0.51 (0.57)	0.53 (0.54)
CaO	0.38 (0.44)	0.62 (0.69)	0.52 (0.53)
Na ₂ O	0.20 (0.23)	0.19 (0.21)	0.18 (0.18)
K ₂ O	1.33 (1.56)	1.45 (1.61)	1.57 (1.59)
P ₂ O ₅	0.05 (0.06)	0.09 (0.10)	0.05 (0.05)
Total Impurities	3.93 (4.49)	4.79 (5.32)	4.65 (4.72)
Total	83.30 (100.00)	90.19 (100.00)	98.37 (100.00)

Conclusions

Class C fly ash can not be utilized to synthesize mullite material because the occurrence of high levels of calcium and sodium significantly reduce the refractoriness of the resulting mullite. In addition, as-received Class F fly ash is not suitable for synthesizing low thermal expansion coefficient mullite materials. However, fly ash beneficiated by the process developed in this research can be utilized to synthesize mullite with water absorption, density, refractoriness, thermal expansion coefficient, and fracture toughness that are comparable to commercial mullite material.

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